CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 Need of drying for agricultural application

According to the Food and Agriculture Organisation (FAO), approximately two third of the global food production is consumed and rest is wasted. With the global population expected to reach 10.5 billion by 2050, this waste poses a serious problem. However, this loss has the potential to supply the food needs of the future if handled and controlled successfully. In the developing nations, substantial post-harvest losses occur in fruits and vegetables that have less shelf-life. These losses are primarily attributed to factors that occur on-farm and between different stages of the distribution process. They include field losses, farmers' decisions to abandon harvesting due to challenging market conditions, losses during the farm-to-market transition, lack of storage space, and inadequate processing capabilities [1]. Prior to the development of canning or freezing, drying was the primary method for long-term food preservation. The use of drying to preserve grains became common after the advent of agriculture and a rise in human reliance on cereals [2]. Drying is necessary because agricultural products need a low moisture content during storage to prevent deterioration, yet a high moisture level after harvesting reduces losses. Warm temperatures and high moisture levels accelerate insect and mould growth and product breathing. High-moisture products are more likely to grow fungus and toxic compounds during storage. Drying of agricultural product's helps in lowering the moisture content which suppresses yeasts, moulds, and germs growth, and allows the product to be stored for longer duration. It additionally helps farmers with a higher market value of the product, early harvest planning, viability of seeds maintenance, and other aspects [3]. Drying food and agricultural products in the open air under the sun is a popular and inexpensive practise, particularly in tropical regions. There are, however, some limitations to this approach. It takes a lot of time and effort and requires a huge area. Furthermore, dust, rain, wind, bugs, and rodents are especially likely to damage the drying process and reduce its effectiveness. In response to which farmers' incomes fall and their output drops. [4].

Energy consumption in the industrial sector is typically between 12 and 20%, with the drying process being one of the most energy-intensive processes. In response to increasing environmental concerns, it is preferable for all industries to reduce their energy consumption. There are numerous methods to reduce the energy consumption of dryers [5, 6]. Spray, freeze, vacuum, tray, rotary, fixed bed, fluidized bed drying, and many others are all examples of conventional food dryers. Excessive drying or under-drying due to lengthy or inadequate or irregular exposure to the drying platform, poor drying performance and high operating costs, significant colour alteration, and dependence on fossil fuel-based energy that emits greenhouse gases are few of the issues with conventional dryers [7]. Sunlight emits energy of around 3.8×10^{23} kW, out of which approximately 1.8×10^{14} kW is absorbed by the earth. Even transforming 0.1% of the total of this energy with 10% efficiency would be equivalent to nearly four times the entire world's electrical power generation of roughly 3 TW [8]. As a result, solar energy is perhaps the most potential source of clean energy. It is ample in quantity and can be employed to supply the world's energy demands. Due to increasing demand for energy and the adverse environmental effects of petroleum and natural gas, industrial applications of solar energy are more commonly acknowledged than previously as a source of alternative energy [9]. Solar energy would provide various social, environmental, and economic benefits, as well as promote sustainable development, job creation, and help keep energy prices steady [10].

Overall, the importance of solar energy and its application for solar drying cannot be overstated. The application using solar energy in drying and heating is projected to become increasingly common in the future as demand for renewable energy sources grows.

1.2 Solar energy resource of India

India receives a lot of sunlight because it is a tropical nation that lies in the sunny belt little above the equator. For the various regions of the country, the average daily sun radiation ranges between 4 to 7 kWh/m^2/day as shown in Fig. 1.1. A typical year has 250–300 days with clear skies. As a result, it receives roughly 5000 trillion kWh from the sun each year. The annual variation in global radiation is between 1600 and 2200 kW/m^2 with Rajasthan and northern Gujarat and parts of Ladakh region receiving the most radiation on an annual basis and the least in the north-eastern part of India [11-14].

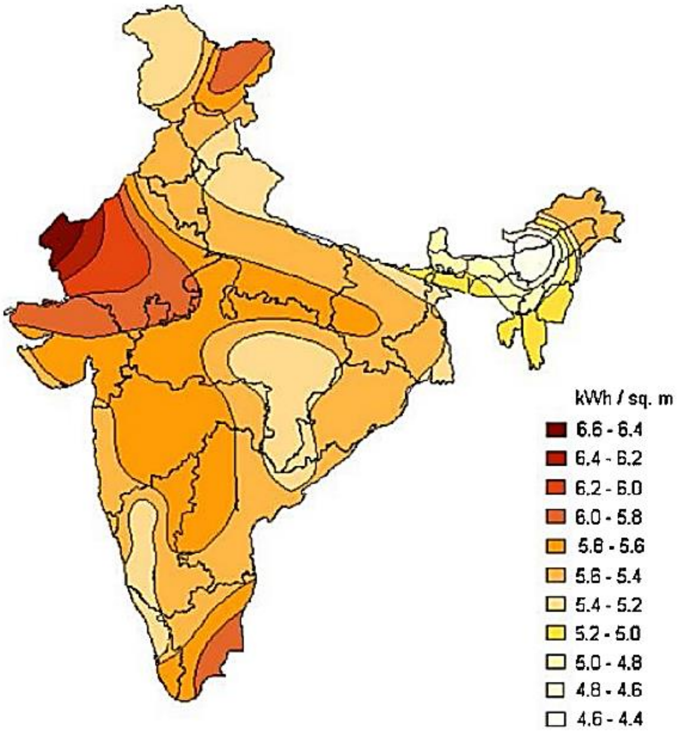


Fig. 1.1: Physical map of solar radiation of India [14]

1.3 Solar drying technology

Solar drying is a method of drying crops, fruits, vegetables, and other agricultural goods by utilising solar radiation. In rural areas, where there is limited access to electricity or fossil fuels, solar drying can be an effective and sustainable method for preserving and processing crops. Solar drying has several advantages over traditional drying methods, including lower operating costs, reduced dependence on fossil fuels, and improved product quality. Solar dryers are simple to construct and operate and can be made using locally available materials. Solar dryers are often made up of a rectangular or tilted surface covered in a transparent material, like glass or polycarbonate or plastic material, that enables solar radiation to pass through and warm the drying section. The drying chamber typically is made of a heat-absorbing material, such as metal or black-painted wood, which absorbs the heat from the sun and transfers it to the drying products. Different types of solar dryers can be generically categorised. In general, four main types of solar dryers (solar dryers, indirect solar dryers, mixed-mode solar dryers, and hybrid) that operates primarily using a forced or natural air circulation mode are successfully employed to dry agricultural goods [15,16].

The item that needs to be dry is placed inside an enclosure with a transparent cover in direct solar dryers. The product and the interior surfaces of the drying chamber absorb solar energy, generating heat. The item being dried is not exposed directly to the sun's light in indirect solar dryers. The product is dried using air that are heated in a solar collector. Solar dryers that use both direct and indirect energy are known as mixed-mode dryers. Hybrid systems that combine solar energy with various forms of energy are one type of specialised dryers/drying systems [3]. During controlled drying, it is common to regulate factors including temperature of air, humidity, rate of drying, moisture content of product, and external wind speed. The design of solar dryers is quite adaptable due to availability of wide range of design configurations [17]. New, and more cost-effective solar dryers are ideal for meeting the drying needs of crops, vegetables, and fruits without sacrificing quality. Different solar dryer designs have been debated and researched for decades. Solar dryers are typically designed for certain items and quality requirements. The greenhouse dryer, indirect dryer, direct (active and passive) dryer, cabinet dryer, tunnel dryer, chimney dryer, multiple pass dryer, hybrid dryer, solar auxiliary unit hybrid dryer, solar-thermal storage hybrid dryer, the solar-geothermal hybrid dryer, the solar-heat pump hybrid dryer, and the solar-chemical heat pump hybrid dryer are all examples of the many ways in which solar dryers have evolved [18].

1.4 Application of PCMs in solar drying

Despite recent advancements in the field of solar drying technology, one of the primary drawbacks for solar drying devices is the sporadic and unpredictable character of sunlight, which necessitates the use of appropriate thermal energy storage (TES) for proper management of solar thermal device operation by conserving extra energy during peak times to be utilised later when the strength of sunlight is insufficient. In this context, Phase change material (PCM) is a promising intermediate solar thermal storage media as it can store solar power as either the sensible or latent heat within the material, or a combination of both [19,20]. ` Among different TES techniques, PCM based latent heat storage (LHS) is considered as an attractive option due to some advantages such as higher energy storage density and capability to store and release thermal energy at relatively constant temperature. However, selection of PCM is one of the critical aspects of the success of PCM based TES. Various criteria such as thermodynamic, kinetic, chemical, and economy governs the selection of PCM. Depending upon different applications and to determine which PCM to be used, we look at its melting temperature, enthalpy of fusion, specific heat, density, and thermal conductivity, among other thermophysical parameters [21-25].

The arrangement of PCM as thermal energy storage medium in solar dryers can be built-in PCM with solar collector, separate PCM heat exchanger and sometimes integrated inside the drying chamber [26-28]. There is currently a shortage of commercially acceptable PCMs for solar drying applications. However, in general, the higher cost of these materials is a significant disadvantage that limits their efficacy in TES systems. As a result, using fatty acids (commercial grade) as form stable PCM increases their viabilities in comparison to their low cost for TES applications. In terms of melting temperature and latent heat of fusion, the investigated fatty acids lauric acid, myristic acid, palmitic acid, stearic acid, and acetamide are potential, abundant, and commercial materials for heat storage in TES systems [29]. The condition for successful solar drying is the ability to maintaining drying temperature range of 40ºC to 60ºC that is found to be sufficient for most of the food products to retain their flavour, aroma, texture, and nutrition values. Therefore, the minimum melting temperature of the PCM should be 5–10 ºC higher than the desired temperature of the heat transfer fluid (HTF). A decent solar dryer design must ensure that the drying air maintains a constant temperature of 10-25 ºC above the ambient temperature. This is required to prevent the dried object from reabsorbing moisture throughout the night, when the air temperature drops, and humidity rises due to a lack of solar radiation [30]. The storage of solar thermal energy using PCM in solar drying is found to be beneficial in reducing heat losses, improving system heat conductivity and reduces the time between energy supply and energy demand, thereby playing an important role in energy conservation and improves the solar drying energy systems. Using PCM in solar dryers improves system reliability and also ensures continuous drying of agricultural products even after sunlight hours and improve the thermal efficiency of the drying system. PCM ensures that products are dried faster, and the products are of higher quality in terms of texture, colour, and nutritional value [28, 31].

The use of PCM resulted in a 6.25-21.87% reduction in the drying time of tomato slices. For the final stages of the drying process, the drying rate of the slices increased. Higher thermal efficiency (40.20%) and overall drying efficiency (25.72%) were obtained at certain placements (d) of PCM at the collector due to the amount of stored thermal energy and shorter drying time. Specific energy consumption for drying tomato slices with PCM was reduced by 7.29-18.97% when compared to drying without PCM [32].

In general, PCMs have significant potential to increase efficiency in energy use and decrease GHG emissions across a wide range of sectors. Overall, PCMs have great potential in improving energy efficiency and reducing greenhouse gas (GHG) emissions in various industries. The potential of PCM integrated solar collectors to increase the energy efficiency of solar thermal systems has garnered a lot of interest lately. Integrating PCM into solar collectors can help to reduce heat loss and boost TES capacity due to the material's ability to store substantial amounts of thermal energy during phase transition processes.

1.5 Importance of sustainable technology in agricultural product processing

Currently, 7–8% of global GHG emissions come from the agri-food industry's usage of fossil fuel inputs (with agricultural methane and nitrous oxide emissions making up nearly double this proportion). Many processing plants use more than half as much energy as they need to because of inadequate energy efficiency measures, antiquated technology, and a lack of understanding. This is an excellent opportunity to cut back on energy consumption and production of GHG [33]. Large amounts of energy are often needed in the processing of agricultural products for purposes like drying, heating, chilling, and running machinery. Using renewable energy sources, we may create environmentally friendly alternatives to conventional farming methods. Investors should be current on all technological developments. Using renewable energy sources in farming and feeding the world can lead to cost savings, efficiency gains, and government subsidies [34]. The typical food drying process consumes a lot of high-quality energy, which can be saved by adopting solar food drying techniques, which reduces greenhouse gas emissions in the atmosphere. The widely utilised open sun-drying process produces low-quality dried products and some food product loss owing to a variety of environmental variables, which can be reduced by using solar dryers for food drying [35].

Use of renewable energy sources for process heating is increasing due to concern for environmental sustainability. Commercial solar dryers are such an example resulted by intensive research and development efforts in the areas of solar thermal applications. There are also successful research efforts on solar drying of agricultural products. Drying of agricultural produces helps in increasing the shelf life, reduction of post-harvest loss and valorisation of agricultural products to create scope for farm-based entrepreneurship. There are several advancements in agricultural solar dryers including application of thermal energy management. Promising features of phase change materials (PCM) based solar dryer including additional gain of heat are conclusively evidenced through earlier research. Use of PCM for solar thermal energy management has been relatively a new but promising concept. However, it requires further attention as evidenced by limited availability of PCM integrated solar dryer.

1.6 Motivation and gap of research

Despite the growing interest in PCM integrated solar collectors, there are research gaps that needs to be addressed. The research area left for further investigations may include the following.

(a) PCM selection and optimization

PCMs are versatile materials that can be utilised to improve energy efficiency, reduce emission of greenhouse gases, and boost the performance of various solar technologies. However, there has been limited research conducted on the use of various types of PCM in solar drying application. Most of the previous studies used only paraffin wax serving as PCM due to its advantageous properties. There are a variety of PCMs available, each with distinct properties that influence their suitability for use in solar dryers. To optimise the performance of solar dryers, it is crucial to identify several numbers of PCMs that are suitable for use in solar collectors/dryers.

(b) Long-term stability and compatibility

The inadequate information on PCM's long-term thermal stability, may lead to selection of PCM that degrade and lose TES capacity, and reduces solar collector efficiency. Because of discrepancies between published data on PCM thermophysical properties and actual chemical properties, characterising PCM for thermal stability is crucial during the selection process of PCM. The best metal container for integration with the solar dryer/collectors must be tested for PCM compatibility through corrosion tests as corrosive metal may lead to shorter lifetime of PCM based solar collectors. Thus, more investigation is required to evaluate the reliability and compatibility of PCM for solar collectors in real-world operating conditions to explore the comprehensive information about the potential PCM candidates for use in solar collectors/dryers.

(c) System integration and design

PCM integrated solar collectors require specialized design considerations to maximize their performance. More research is needed to develop optimal system designs that integrate PCM materials into solar collectors in the most efficient and effective way. PCM integrated solar dryers require specialized design considerations to maximize their performance. Many researchers have investigated the design, development, and performance of many types of solar air heater (SAH); however, further research is required for precise design of SAHs with integrated PCM based on variables such as standard absorber area, desirable mass flow rate of air, and preferred PCM sizing to design highly efficient solar collector/dryer.

(d) Techno economic and environmental performance

The solar dryer or collector systems based on PCM need to be energy and exergy efficient. The design should be economical for the specific purpose and the material used should be environment friendly. The energy analysis is essential to study system efficiency since it is important for evaluating the real behaviour of system containing varying energy losses and internal irreversible effects. Exergy analysis is a highly significant tool for determining the best configuration of solar dryers for efficient utilisation of solar energy. The exergy study has been very important to overcome or bypass many design and operational failures. The economic and environmental study of solar dryer also remains important aspects to develop techno- economically efficient PCM based solar dryers.

1.7 Objectives of research

Following objectives are set based on the need for comprehensive understanding of PCM integrated solar dryer for agricultural product.

1. PCM for solar drying application: Selection and assessment for thermal stability and compatibility.
2. Design, development, and performance analysis of PCM integrated solar air heater (SAH).
3. Performance study of phase change material solar dryer (PCMSD): Energy, exergy, economic and environmental analysis.

1.8 Organization of the Thesis

The text of the thesis is organized as below.

Chapter 1: Introduction

This Chapter highlights general introduction of the need of solar drying for agricultural application, solar energy resource of India, solar drying technology, application of PCMs in solar drying, importance of sustainable technology in agricultural product processing, significance and motivation of the research and objectives of the research.

Chapter 2: Literature review

This Chapter includes literatures on the relevant aspects of the current research work *viz*., Characterization of PCM and its importance for selection vis-à-vis applications, arrangement for integration of PCMs in solar heating applications, thermal stability: A critical parameter for selection of PCMs, **c**ompatibility of PCMs with construction material of storage device, applications of PCMs in solar air heaters and solar dryer, application of modelling and simulation software for SAH design and economic and environmental analysis solar dryer are presented.

Chapter 3: PCMs for solar drying application: Selection and assessment for thermal stability and corrosivity

The study in the Chapter includes identification and selection of PCM through multi attribute decision matrix, long-term thermal stability of the selected PCMs investigated using thermogravimetry analysis (TGA) and differential scanning calorimeter (DSC) techniques, compatibility of the selected PCMs with the container material or the metal specimens were studied by corrosion test, microscopic imaging, and surface roughness profiling.

Chapter 4: Design, development, and performance analysis of PCMSAH

This Chapter includes study to estimate the design (length of absorber, PCM sizing) and operational parameters (air mass flow rate) for design of PCMSAH, parametric investigation based on the energy analysis, PCM properties, shape of the proposed SAH, and climatic conditions of the testing location. Development of the SAH system and comparison of the performance between SAH with and without PCM. It also includes uncertainty analysis for thermal efficiency of PCMSAH.

Chapter 5: Energy, exergy, economic and environmental analysis of the PCMSD

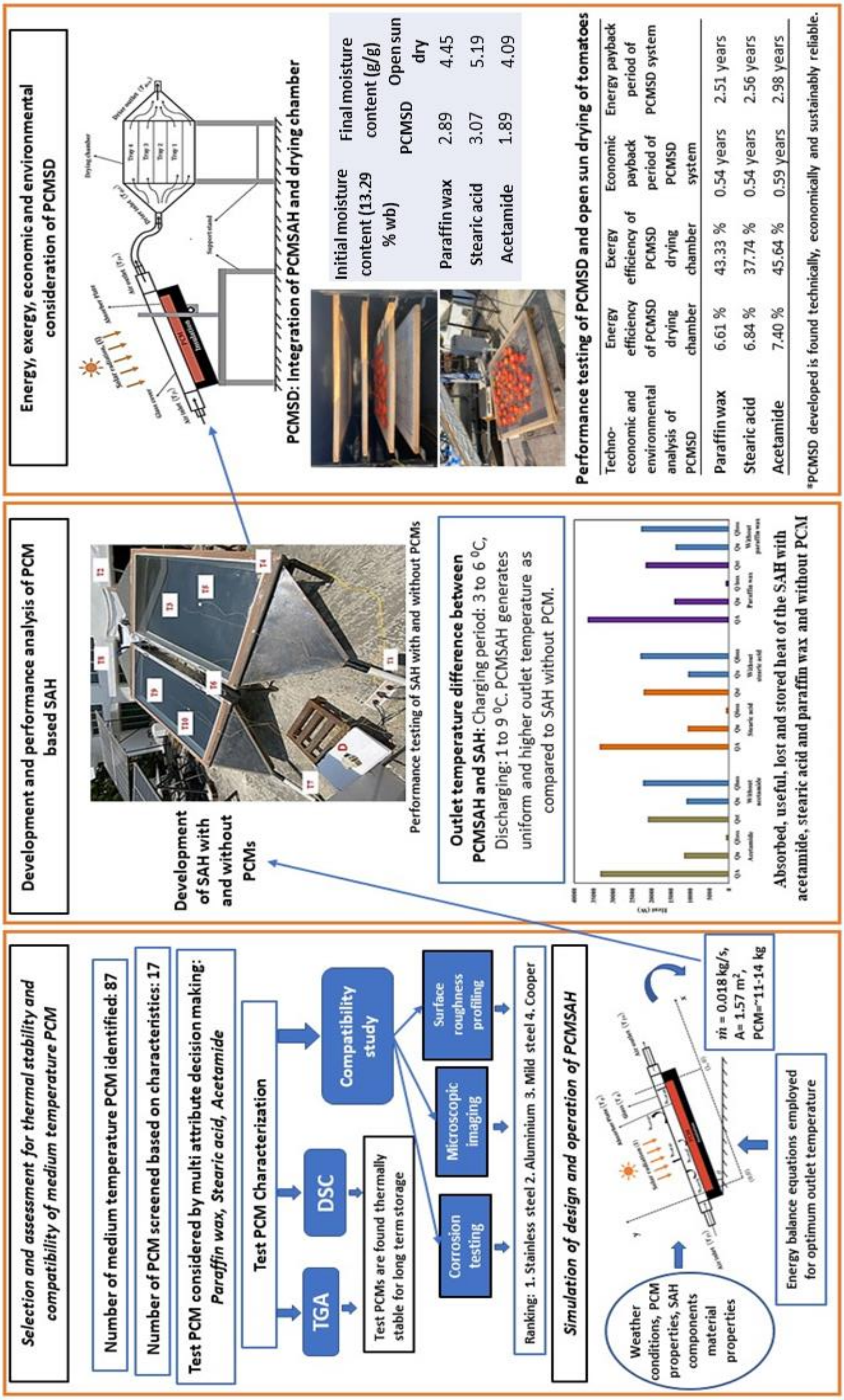
This Chapter involves the study of the developed PCMSAH from the previous chapter by integrating a drying chamber in detail. The study involves performance of developed phase change material solar dryer (PCMSD) by executing tomato drying experiments with three different PCMs. The detailed study on drying characteristics of tomato is presented. PCMSD collector and drying section energy and exergy analyses are presented. To determine whether the PCMSD is economically and environmentally feasible for technology transfer to end users like farmers and other beneficiaries, an annualized cost method and payback time economic analysis and an embodied energy, annual CO_2 mitigation, and carbon credit environmental analysis are performed.

Chapter 6: Summary and conclusions

This chapter provides a basic summary of the overall findings and conclusions, including new directions that have developed from this work to address in future work. These new directions are addressed in this chapter.

Following the appendix and the list of publications comes at the end of conclusion of the Thesis.

1.9 Graphical representation of the Thesis



References

[1] Srivastava, A., Anand, A., Shukla, A., Kumar, A., & Sharma, A. Performance evaluation of an industrial solar dryer in Indian scenario: A techno-economic and environmental analysis. *Clean Technologies and Environmental Policy*, 24(9): 2881-2898, 2022.

[2] Bradford, K. J., Dahal, P., Van Asbrouck, J., Kunusoth, K., Bello, P., Thompson, J., & Wu, F. The dry chain: Reducing postharvest losses and improving food safety in humid climates. *Food Industry Wastes* (pp. 375-389). Academic Press, 2020.

[3] Sharma, V. K., Sharma, S., & Garg, H. P. Mathematical modelling and experimental evaluation of a natural convection type solar cabinet dryer. *Energy Conversion and Management*, 31(1): 65-73, 1991.

[4] Ekechukwu, O. Va, and Brian Norton. "Review of solar-energy drying systems II: an overview of solar drying technology." *Energy conversion and management* 40.6:615-655, 1999.

[5] Raghavan, G. V., Rennie, T. J., Sunjka, P. S., Orsat, V., Phaphuangwittayakul, W., & Terdtoon, P. Overview of new techniques for drying biological materials with emphasis on energy aspects. *Brazilian Journal of Chemical Engineering,* 22:195-201, 2005.

[6] Mujumdar AS, Law CL. Drying technology: Trends and applications in postharvest processing. Food and Bioprocess Technology. 3(6):843-852, 2010.

[7] Mujumdar, A. S., & Law, C. L. Drying technology: Trends and applications in postharvest processing. *Food and Bioprocess Technology*, 3:843-852, 2010.

[8] World Energy Council 2013, World Energy Resources: Solar, <https://www.worldenergy.org/assets/images/imported/2013/10/WER_2013_8_Solar_revised.pdf> (accessed on 10.05.2023).

[9] Mekhilef, S., Faramarzi, S. Z., Saidur, R., & Salam, Z. The application of solar technologies for sustainable development of agricultural sector. *Renewable and sustainable energy reviews*, 18: 583-594, 2013.

[10] Maka, A. O., & Alabid, J. M. Solar energy technology and its roles in sustainable development. *Clean Energy*, 6(3):476-483, 2022.

[11] Arjunan, T. V., Aybar, H. Ş., & Nedunchezhian, N. Status of solar desalination in India. *Renewable and Sustainable Energy Reviews*, 13(9):2408-2418, 2009.

[12] Ministry for New and Renewable Energy, Solar Energy. <https://mnre.gov.in/solar/current-status/>, 2023 (accessed on 21.03.2023).

[13] Khare, V., Nema, S., & Baredar, P. Status of solar wind renewable energy in India. *Renewable and Sustainable Energy Reviews*, 27:1-10, 2013.

[14] Singh, Y., & Pal, N. Obstacles and comparative analysis in the advancement of photovoltaic power stations in India. *Sustainable Computing: Informatics and Systems*, 25: 100372, 2020.

[15] Visavale, G.L. Principles, Classification and Selection of Solar Dryers. In Hii, C.L., Ong, S.P., Jangam, S.V. and Mujumdar, A.S., editors, *Solar drying: Fundamentals, Applications and Innovations*, pages 1-50, ISBN - 978-981-07-3336, 2012.

[16] Fudholi, A., Sopian, K., Ruslan, M. H., Alghoul, M. A., & Sulaiman, M. Y. Review of solar dryers for agricultural and marine products. *Renewable and sustainable energy reviews*, 14(1):1-30, 2010.

[17] Srivastava, A., Anand, A., Shukla, A., Kumar, A., & Sharma, A. Performance evaluation of an industrial solar dryer in Indian scenario: A techno-economic and environmental analysis. *Clean Technologies and Environmental Policy*, 24(9):2881-2898, 2022.

[18] Ahmadi, A., Das, B., Ehyaei, M. A., Esmaeilion, F., Assad, M. E. H., Jamali, D. H., & Safari, S. Energy, exergy, and techno-economic performance analyses of solar dryers for agro products: A comprehensive review. *Solar Energy*, 228:349-373, 2021.

[19] Dincer, I. Evaluation and selection of energy storage systems for solar thermal applications. *International journal of energy research*, 23(12):1017-1028, 1999.

[20] Agrawal, A., & Sarviya, R. M. A review of research and development work on solar dryers with heat storage. *International Journal of Sustainable Energy*, 35(6):583-605, 2016.

[21] Sharma, S. D., & Sagara, K. Latent heat storage materials and systems: a review. *International journal of green energy*, *2*(1):1-56, 2005.

[22] Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable energy reviews*, 13(2):318-345, 2009.

[23] Paris, J., Falardeau, M., & Villeneuve, C. Thermal storage by latent heat: a viable option for energy conservation in buildings. *Energy Sources*, 15(1):85-93, 1993.

[24] Singh, S., Gaikwad, K. K., & Lee, Y. S. Phase change materials for advanced cooling packaging. *Environmental Chemistry Letters*, 16:845-859, 2018.

[25] Kumar, A., & Shukla, S. K. A review on thermal energy storage unit for solar thermal power plant application. *Energy Procedia*, 74:462-469, 2015.

[26] Shalaby, S. M., Bek, M. A., & El-Sebaii, A. A. (2014). Solar dryers with PCM as energy storage medium: A review. Renewable and Sustainable Energy Reviews, 33, 110-116.

[27] Manirathnam, A. S., Kumar, K. S., Sudhakar, S., Balaji, S. V., Kumar, S. S., & Vibishan, R. Improving the efficiency of solar drying unit with PCM (Paraffin wax). *In Journal of Physics: Conference Series, IOP Publishing*, 2070,1, 012213, November 2021.

[28] Sandali, M., Boubekri, A., & Mennouche, D. Improvement of the thermal performance of solar drying systems using different techniques: a review. *Journal of Solar Energy Engineering*, 141, 5, 050802, 2019.

[29] Jain, A., Kumar, A., Shukla, A., & Sharma, A. (2017). Development of Phase Change Materials (PCMs) for solar drying systems. Solar Drying Technology: Concept, Design, Testing, Modeling, Economics, and Environment, 619-633.

[30] Patel, J., Andharia, J., Georgiev, A., Dzhonova, D., Maiti, S., Petrova, T., ... & Panyovska, S. A review of phase change material based thermal energy accumulators in small-scale solar thermal dryers. *Bulg Chem Commun*, 52, 53-64. 2020.

[31] Sudhakar, P. A review on performance enhancement of solar drying systems. *In IOP Conference Series: Materials Science and Engineering, IOP Publishing*, 1130, 1, 012042, April 2021.

[32] Ebrahimi, H., Akhijahani, H. S., & Salami, P. Improving the thermal efficiency of a solar dryer using phase change materials at different position in the collector. *Solar Energy*, 220, 535-551, 2021.

[33] Sims, R., Flammini, A., Puri, M., & Bracco, S. Opportunities for agri-food chains to become energy-smart. *FAO USAID*, 2015.

[34] Gorjian, S., Fakhraei, O., Gorjian, A., Sharafkhani, A., & Aziznejad, A. Sustainable Food and Agriculture: Employment of Renewable Energy Technologies. *Current Robotics Reports*, 3(3): 153-163, 2022.

[35] Sharma, M., Atheaya, D., & Kumar, A. Recent advancements of PCM based indirect type solar drying systems: a state of art. Materials Today: Proceedings, 47, 5852-5855, 2021.