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A COMPREHENSIVE REVIEW ON SOLAR DRYERS AND PHASE CHANGE MATERIALS FOR MUSHROOM DRYING

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Abstract- Solar energy is the most plentiful source of renewable energy. All other sources of energy on earth are dwarf in comparison to the sunlight that strikes the earth each day. The energy used for various purposes whereas the solar dryers have so many advantages in the agriculture and food. But like everything solar dryer has its own pros and cons. Some major drawbacks of using a solar dryer are that it can only be used during the daytime, so the drying of food crops during nighttime is very difficult and the initial setup cost may be high. This problem can be solved by integrating thermal storage devices in solar dryers. These thermal storage devices are used to store heat when no sunlight is available. One of the most efficient way of storing thermal energy is using Phase Change Material in solar dryer. These materials absorb, store, and release heat energy during a phase transition either from solid to liquid or liquid to solid at a constant temperature.
Keywords: Solar energy, dryers, food crops, thermal storage device and phase change material.

1. INTRODUCTION

In India, 70% of population depend on agriculture for their livelihood and of this population most farmers cannot afford hi-tech facilities and equipment which is a major problem. In many rural areas of India, the farmers grow fruit and vegetables and they have to be sold in the market immediately after harvesting because they are very perishable. According to the Food and Agriculture Organization (FAO) of the United Nations, approximately one-third of all food produced in the world is lost at some stage between production and consumption, totalling 930 million tons of food per year, out of which 44 million tons counts for mushroom production (FOASTAT, 2023).World production of mushrooms is estimated about 12 million tonnes and the annual growth rate is still above 8 %; India too, though late starter, is fast catching up and the current production has crossed lakh tonne mark with annual growth rate of above 15 %; the venture is no more confined to the seasonal growing in the northern region, it has spread far and wide in the country. At present, the total mushroom production in India is approximately 0.13 million tons. From 2010-2017, the mushroom industry in India has registered an average growth rate of 4.3% per annum. When the production is high, the farmers have to sell the raw product at very low price, which also increases losses [1]. This loss can be managed by the drying of the raw material. The resultant product can be stored for longer time in less volume which the farmer can sell the dried products at higher price in off season [2].

Drying of material means removal of moisture from the raw material. Drying is a two-stage process. In the first stage drying takes place at the surface of the material at a constant drying rate. In the second stage drying takes place in the decreasing manner. Drying is done to increase the shelf life, provide less space for storage and to decrease transportation costs of agricultural products [3]. The Earth's surface receives about 156 petawatts (PW) of solar energy. The Earth's surface can experience direct beam radiation of up to 1000 W at noon on a clear day. Because solar energy is abundant, readily available, and reasonably priced, its popularity been growing [4]and Itis also environmentally friendly. Regardless, the utilization of solar energy to dry fresh food products is one of the oldest preservation techniques used by humans.

The traditional drying methods also called as open sun drying the agricultural produce are to dehydrate the material under direct sunshine. Natural drying takes place under the influence of sunlight and wind and is of three types viz. sun, air and shade drying. In natural drying there is no control over temperature, air flow, humidity and there is also damage caused by birds, rodents, dust, rain, direct exposure to radiation, insect infestations and microorganisms. Due to these factors the overall quality of the dried products is significantly reduced whereas in artificial drying, quality of the dried products is well controlled.

In light of the drawbacks of conventional drying methods, more sophisticated and regulated drying techniques are required in order to reduce post-harvest losses and guarantee improved quality and preservation of dried food and another item. Solar drying systems made of enclosed devices that capture and use solar radiation to raise the inside temperature have been developed as a result of advancements in sun drying procedures. A fundamental distinction between sun drying and solar drying is the use of apparatus to capture and retain solar radiation. Solar drying has become widely used in several industrial areas in addition to agriculture.

When a PCM material absorbs heat it gets converted into liquid state and when it releases heat it gets solidified [5]. Integrating a PCM material in a solar dryer provides a constant source when no sunlight is available and also reduces the heat losses in the drying system [6].Therefore, a solar dryer with a PCM increases the system's dependability, boosts the dryer's thermal efficiency, and results in faster drying rates and higher-quality food products. Using a PCM allows latent heat storage that stores 5–10 times additional heat in contrast to that stored with the use of another heat storage medium. The most economical, efficient, and effective thermal energy storage device is a phase change material (PCM). Because of its substantially greater latent heat of fusion and self-nucleating capabilities, paraffin wax is the most chosen PCM.

2. TRADITIONAL DRYING METHOD

2.1 Sun Drying

In sun drying method, the crop is placed directly on the floor in open area, and left there for a number of days to dry. In this method the process of drying is very slow and there are many usual problems like dust contamination, insect infestation and spoilt products due to rain, loss of product due to birds and animals.

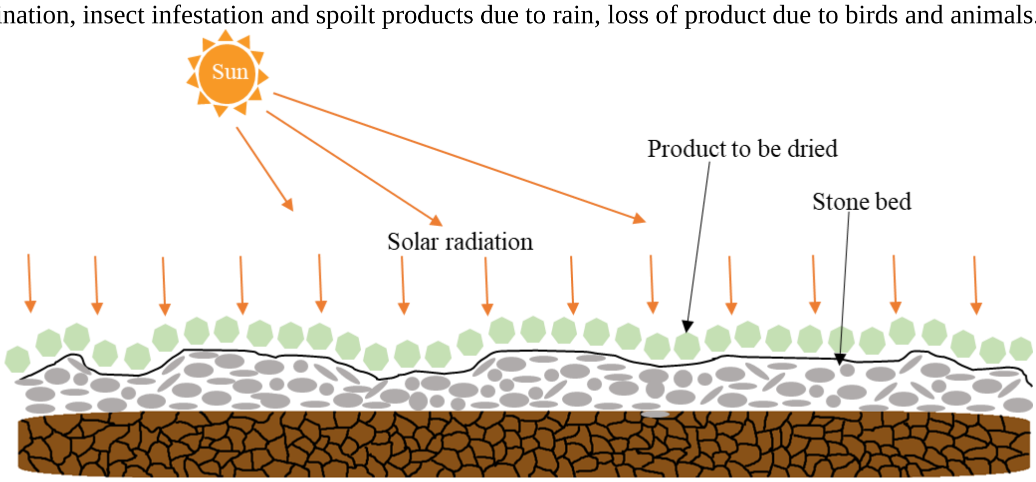

Fig. 2.1 Schematic representation of Sun Drying

Open sun drying also gives us inconsistent results and is also not suitable of the products which require specific drying conditions. Due to its numerous drawback sun drying to be replaced with mechanical dryers, which use fossil fuel to heat drying air and electricity to force dry air through the agricultural products.

2.2 Shade Drying

Shade drying utilizes indirect sunlight, typically by placing the food under a covered area that filters out most of the sun's rays, resulting in a slower drying process but potentially preserving more nutrients and color. The technique uses wind energy to regulate the internal temperature of the shed without adding any extra heat sources and it mostly depends on natural environmental fluctuations. Through a solar panel on top of the shed, sunlight enters the shed throughout the day, creating a heat source for drying. Additionally, the heat source gathered at the top of the sunshade ventilation shed offers thermal protection for the drying process throughout the night. Some of the limitations of shade drying is that it requires more space and longer drying time.

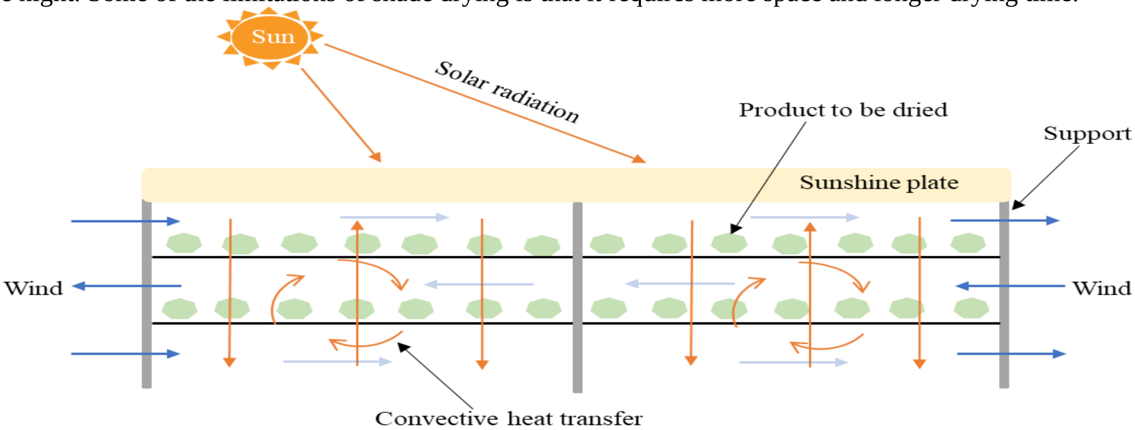

Fig. 2.2 Schematic representation of Shade Drying

2.3 Air Drying

In Air Drying air is used which fastens the speed of drying. It uses low heat and low humidity to evaporate moisture from food. It's a simple, traditional technique that can be done indoors in a well-ventilated space. Air drying is often used for herbs, chili peppers, mushrooms, and nuts preservation. Air is brought into the dryer (by

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a fan in a Forced Type Air Dryer) which then blows the air across a heating source to warm it. The increased water-holding capacity of the heated air is a key factor in drying.

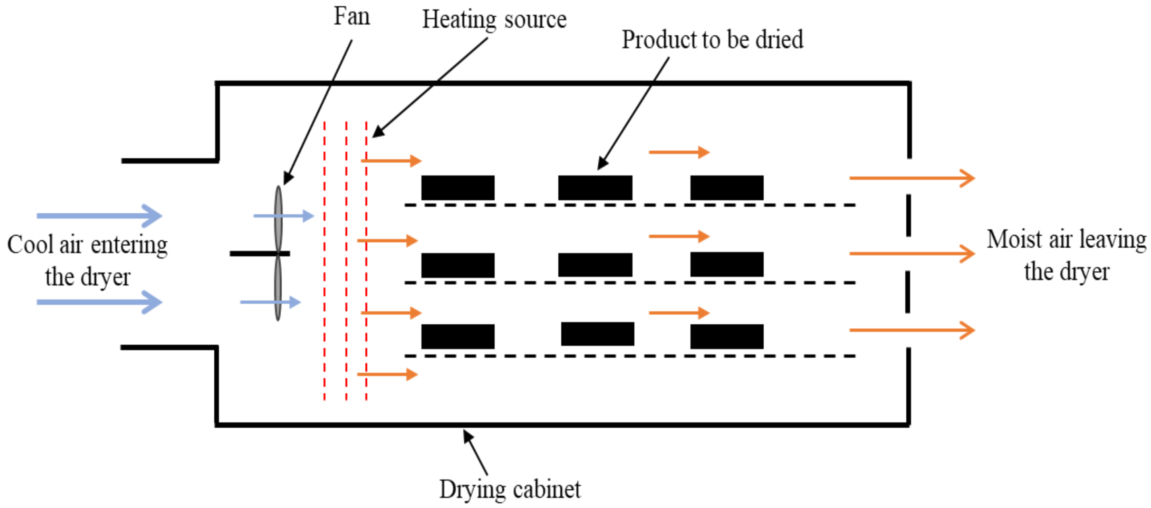

Fig. 2.3 Schematic representation of Air Drying

The heated air then travels to the drying chamber unit where the material to be dried is located. When the heated air passes over the moist surfaces, it picks up moisture. The air then carries the moisture out of the dryer. Air drying has various limitations like low energy efficiency, Quality loss and long drying time, poor quality control. Despite of limitations, natural drying remains the most common method of solar drying. This is because of the energy requirements, which come from solar radiation and the air enthalpy, are readily available in the ambient environment and no capital investment in equipment is required (Sontakke1, 2015).

3. SOLAR DRYING

With the advent of sun drying techniques, systems comprised of closed devices that capture and use solar radiation to raise the temperature within have been developed. The primary distinction between solar and solar drying is the use of machinery to gather and retain solar energy. When compared to typical sun drying, solar dryers offer several benefits, including shorter drying times, more efficiency, better sanitation, healthier final products, and cost-effectiveness[7]. These systems, by utilizing solar energy, provide a more regulated environment for the drying process, improving quality and lowering post-harvest losses.

The basic idea behind how solar dryers operate is that heat is sent from a source to the product being dried, and moisture is made easier to move from the product's surface to the surrounding air. Based on the incidence of solar radiation as an operational concept Solar Dryer can be classified into open sun, direct (with cabinet), indirect or hybrid[8].

3.1 Open Sun Drying

It is also called as natural drying. In this method, solar radiation directly comes into contact with the surface of the crop, which is frequently scattered on the ground.

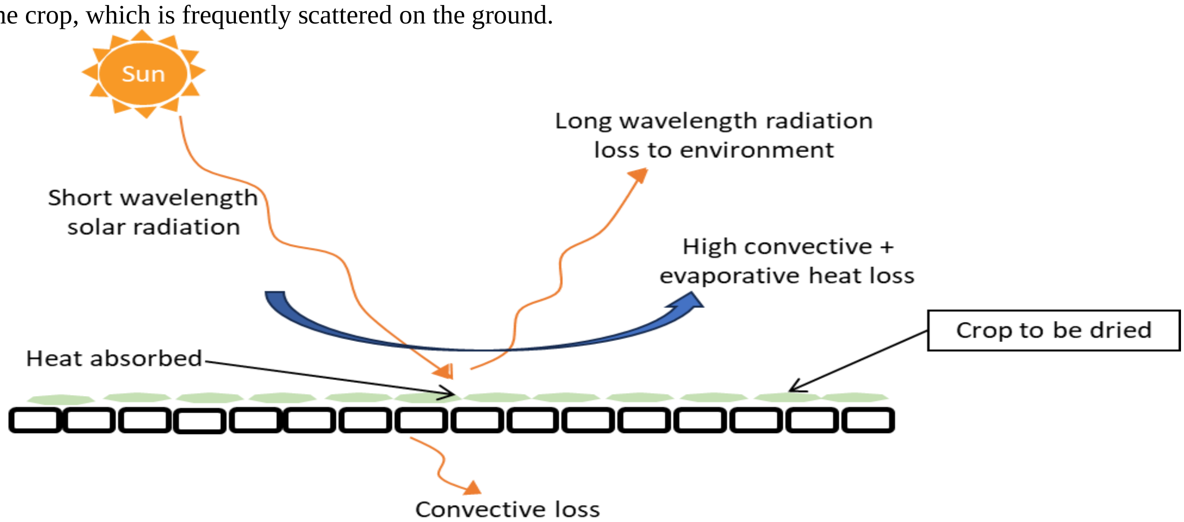

Fig. 3.1 Schematic representation of open Sun Drying

The solar radiation falls directly on the surface of the crop which gets absorbed and gets converted into thermal energy and helps the dehydration of the crop. There are some energy losses which decreases the efficiency of the process.

3.1.1 Direct Solar Drying

The simplest technique is open direct solar drying, which exposes the products directly to the environment. The method's key advantage is that it is extremely cost-effective because no additional fuel is required. However, there are also drawbacks, such as increased product losses due to fungal growth, pests, or unexpected weather conditions. To address these issues with the open drier, consider adding a transparent covering above the drying products. [7] Direct closed solar dryers have a drying chamber, which is an insulated box with a transparent cover made of glass or plastic and air openings that allow air to enter and exit the chamber. The glass reflects a part of the solar radiation back into the environment, while the balance enters the drying chamber and is absorbed in the crop, increasing the temperature inside the chamber. The use of glass minimizes convective losses to the environment. The air passing through the chamber removes moisture from the crop. [7] Direct solar drying systems are grouped into different categories based on their layout and design: tunnel-type, cabinet-type, and greenhouse-type dryers. Each kind has its specific advantages and is appropriate for a variety of applications, based on the type of product being dried, local climate conditions, and drying efficiency requirements.

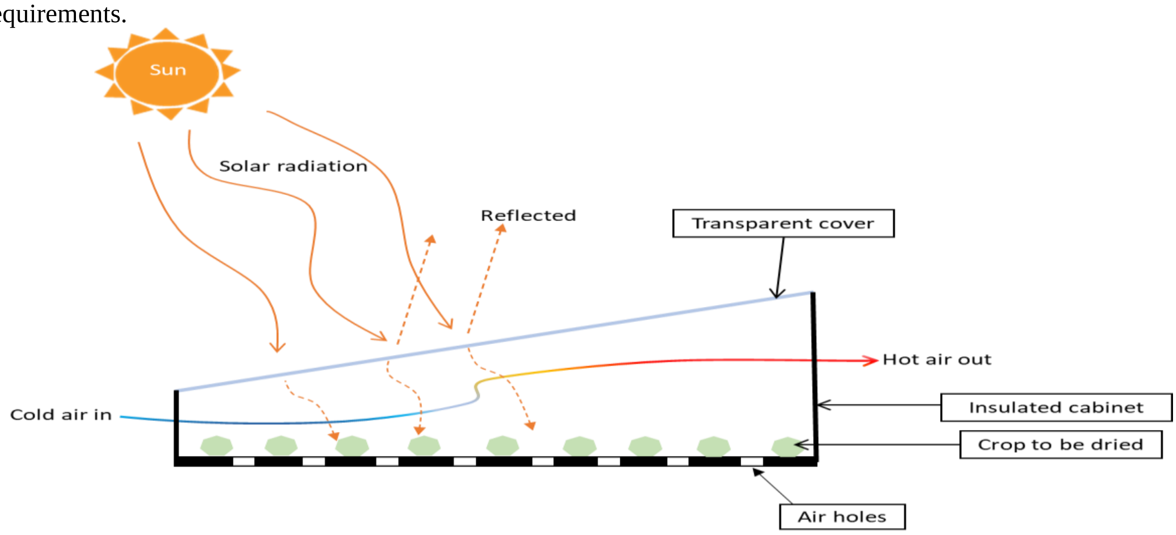

Fig. 3.2 Schematic representation of Direct Solar Drying

3.2 Indirect Solar Drying

The main differences between ISD and DSD are their heat transfer and vapor removal technologies. on indirect solar dryers, crops are arranged on trays or shelves within an opaque drying cabinet in an isolated unit from the solar collector. The solar collector heats the ambient air, which then travels to the drying chamber. The air can be heated actively with a fan or passively via natural convection. The hot air is then directed onto the wet crop, where it evaporates moisture. This is due to a differential in moisture concentration between the drying air and the material's surface. The drying process in indirect sun drying occurs when water is transferred between the product and the moving hot air.

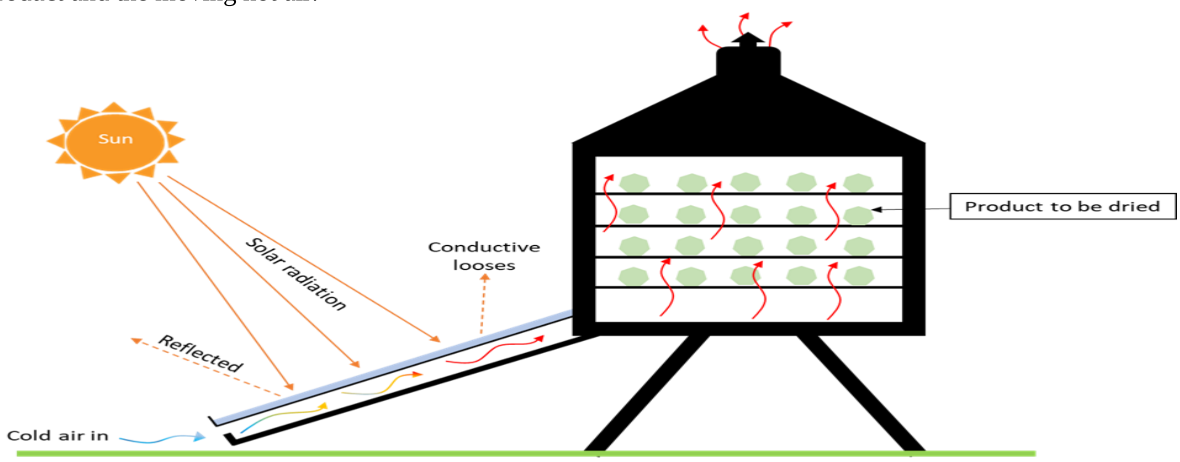

Fig. 3.3 Schematic representation of Indirect Solar Drying

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3.3 Hybrid Drying Techniques

Hybrid drying systems involve multiple dryers (convection, microwave, freeze-drying, and ultrasound.) or multiple modes of heat transmission, as well as two or more stages of drying to accomplish the desired dryness, product quality, drying time, and industrial throughput.[9]. The procedures employed during combined drying include heat transfer, multi-stage and multi-process drying, and the application of additional treatments such as filtration and agglomeration. The following is a breakdown of combination drying processes.

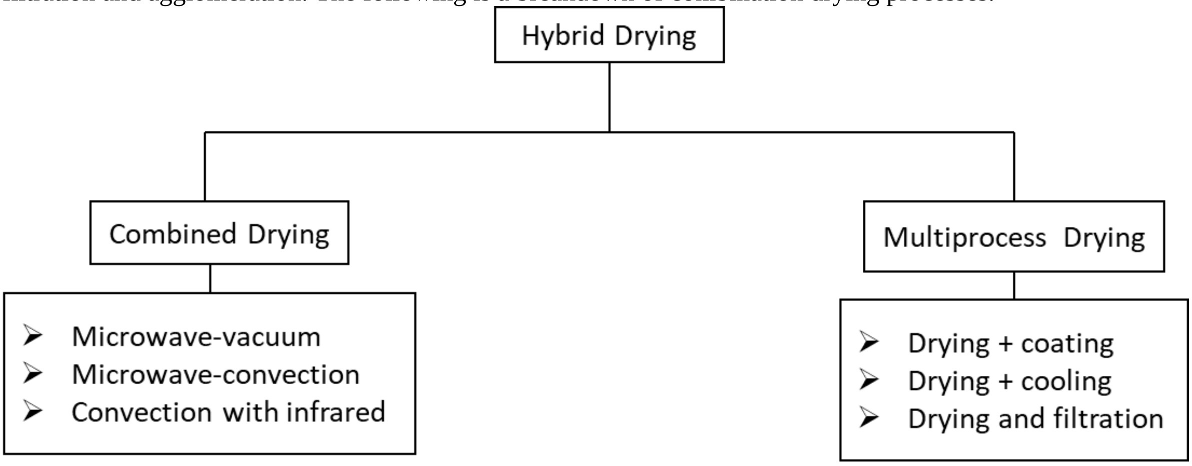

Fig. 3.4 Schematic representation of Hybrid Drying Techniques

Use of combined drying methods lowers the amount of time and increases the rate of moisture removal from the material, so that the raw material is not subjected to long term high temperatures, thereby conserving its nutritional content, color, and structure.[10]. Hybrid dryers can combine several heating processes, such as fossil fuel, gas, biomass, or electric heating, with solar heating. They frequently use photovoltaic (PV) panels to create electricity, which can be integrated into the drying system.

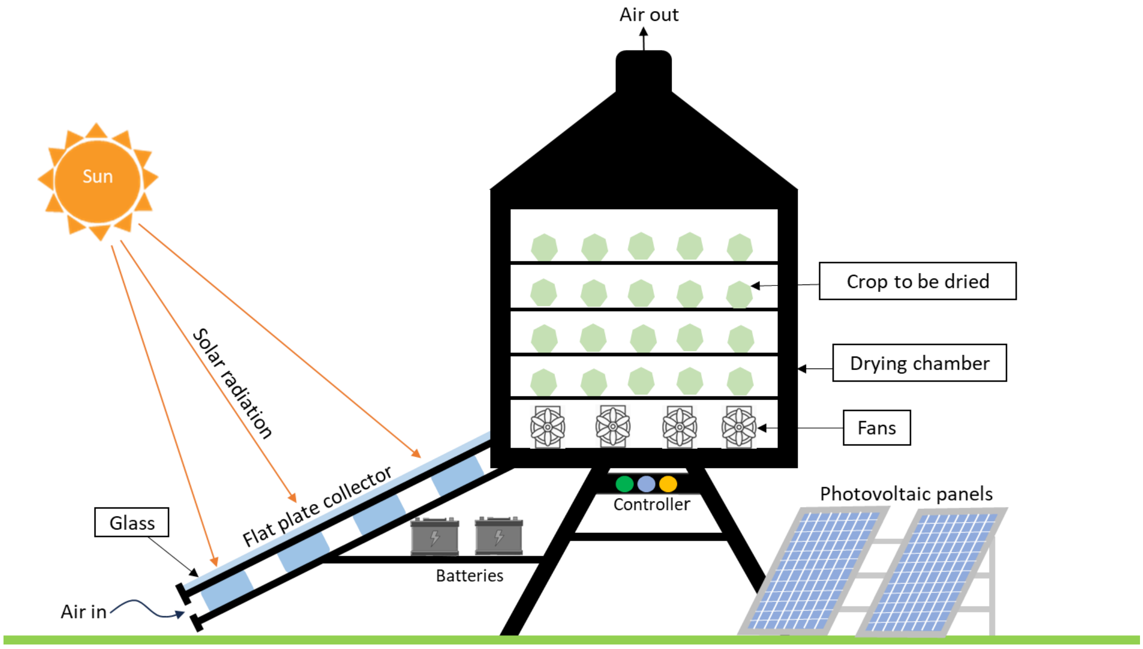

Fig. 3.5 Schematic of working principle of Hybrid (solar–thermal) Drying Method

By combining different energy sources and techniques, hybrid dryers offer more control over the drying process, allowing for better optimization of drying conditions and improved product quality.[7]

3.3.1 Hybrid Solar Drying

A hybrid solar dryer is a kind of solar dryer that augments its energy output with extra energy from other sources, such electric and biomass, or with additional heat sources, like mechanical heat pumps and thermal storage, to help with drying. Both single and combined drying modes are employed with these kinds of dryers. They can be divided several ways, depending on their construction and combination (photovoltaic/thermal (PVT) panels, Solar collectors, Energy storage materials, with Auxiliary unit, the sorption materials, with geothermal waste waters) [11].

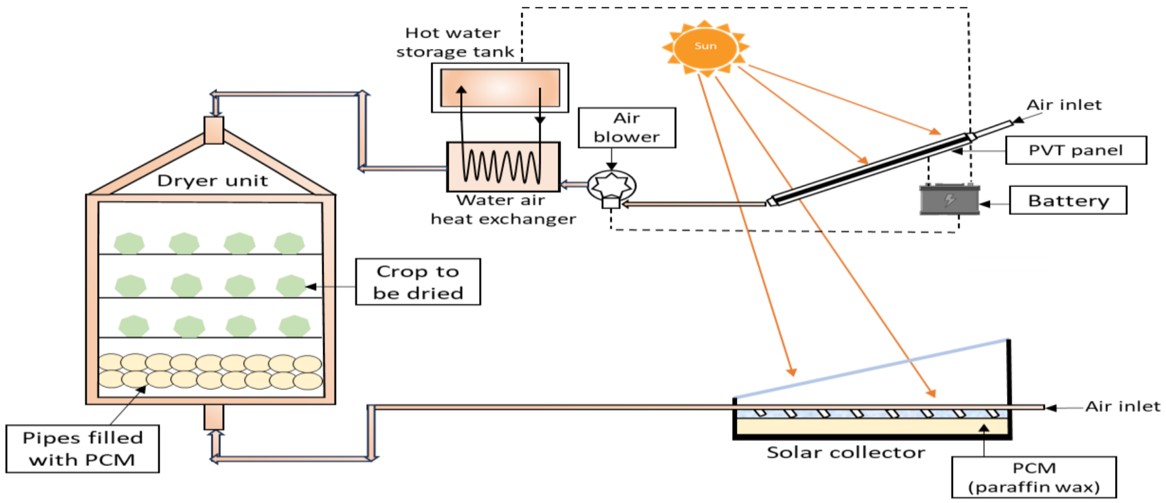

Fig. 3.6 Integrated solar dryer with PCM and injection, powered by PVT Panels and Solar Concentrator

4. RECENT TECHNOLOGICAL ADVANCEMENTS ON SOLAR DRYING

Solar dryers have become increasingly intelligent over time. Smart solar dryers (SSD) have emerged as a result of technological advancements. Solar dryers have transitioned from open-air to smart drying. Smart solar dryers now feature higher levels of intelligence, leading to better performance and efficiency. Arduino boards with ATMEGA controllers are widely used in IoT applications, including drying technologies. PID controllers are the most often utilized controllers in dryer automation. Dryer controls typically regulate temperature and humidity. SSD's economic feasibility has been widely assessed using life cycle cost and life benefit cost metrics. SSD outperforms traditional drying methods in terms of economic benefits.

Because of the limitation of the solar energy only during the day hybrid solar dryers containing material for thermal energy storage are used. These materials absorb the heat from the solar radiation during the day and emit heat when no sunlight is available or during the day resulting into the continuous drying of the crop. Thermal energy can be stored in well-insulated materials by changes in internal energy, such as sensible heat, latent heat, thermochemistry, or a combination these.

Sensible heat storage (SHS) involves heating materials that retain extra solar energy based on their specific heat capacity, mass, and temperature. Generally, water appears to be the best SHS materials due to its high specific heat and inexpensive. Natural materials for energy storage are also used in solar dryers. Some of the readily available natural energy storage materials include reinforced concrete, quartz, bricks, soil, clay, limestone, pebbles, rocks, gravel, sandstone, sand etc. Because solid materials have a higher heat capacity, sensible heat storage in solid state is a preferable choice for storing thermal energy [12].

Latent heat storage (LHS): This type of material stores solar energy at the time of phase transition from solid to liquid or liquid to vapor in the form of latent heat of fusion and vaporization respectively. The phase change materials (PCM) might be organic or inorganic.

Thermochemical energy storage (TCES) is based on the idea that all chemical processes absorb or release heat. This technique stores energy by using high-energy chemical reactions which are completely reversible. It is the process of storing energy through cooling, heating, melting, solidifying, or vaporizing a substance.

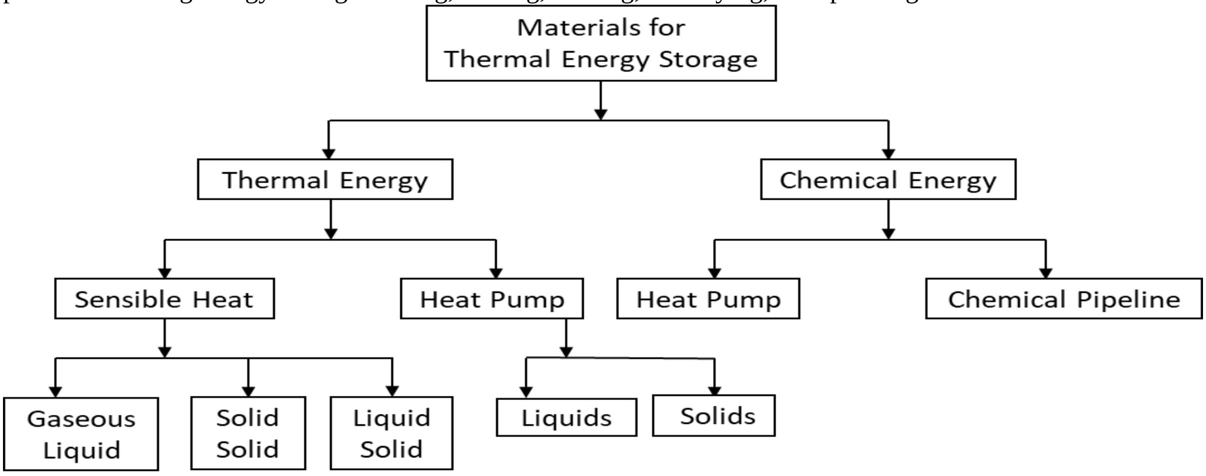

Fig. 4.1 Classification of Thermal Energy Storage Materials

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Latent heat thermal energy storage is a popular option due to its high density of energy per unit volume and mass in an isothermal process, i.e., it stores heat at a steady temperature, which corresponds to the phase-transition temperature of PCM. PCMs emit heat as latent heat during freezing and absorb energy from the surrounding environment during melting. Latent heat storage improves the quality of dried products by supplying heat at a steady temperature [13]. A PCM holds 5-15 times more heat than sensible heat storage materials such as water, masonry, and rock [5].

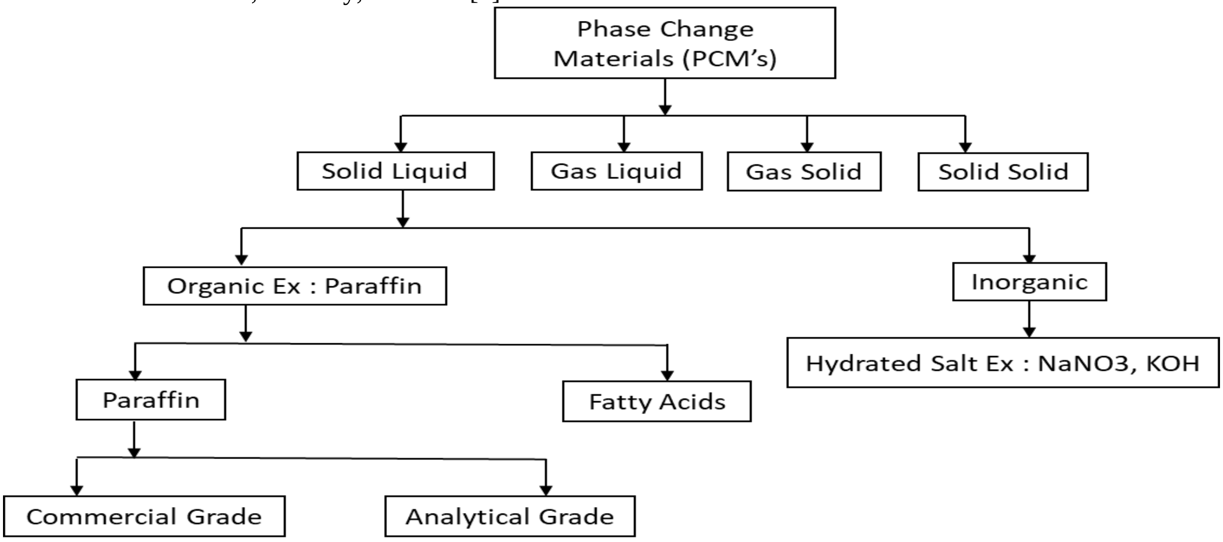

Fig. 4.2 Classification of Phase Change Materials

Paraffin wax is the most-used commercial organic heat storage PCM.[14] Because they show no tendency to segregate, they are chemically stable[15], they not show degradation in thermal properties after repeated 3 melting/freezing cycles, they have high heat of fusion. They are compatible with all metal containers and easily incorporated into heat storage systems [15]. The desire to produce higher-quality products in large quantities is driving the advancement of novel dehydration techniques. This aim can be accomplished by combining solar dryers with different energy storage medium to make high-quality dehydrated foods at a reasonable cost. The combination dryer configuration with PCM and forced-convection gives the best result with the highest dehydration rate and maximum quality among the various dryer categories.

The quality and overall drying duration of the dehydrated mushrooms were affected differently by the various sublimation drying techniques, such as Freeze Drying (FD), Microwave Freeze Drying (MFD), and Atmospheric Freeze Drying (AFD). Approximately 55% of the total water was sublimated during the MFD process, while approximately 60% of the total water was sublimated during the FD process, according to a comparison of death curves [16].

5. MATERIAL INNOVATIONS

In the face of growing environmental risks caused by changes in the climate and global warming, there is a pressing need for new and environmentally friendly energy sources. Phase Change Materials (PCMs) are a potential technology for passive heat regulation in solar dryers. In order to reduce our dependence on fossil fuels, it becomes important to improve thermal performance and develop new thermal energy storage (TES) technologies. This motivates scientists to innovate constantly. Recently, bio-based PCMs composed of renewable elements such as carbohydrates and proteins have received significant interest. Cellulose and its derivatives, chitosan, lignin, gelatin, and starch are examples of bio-based polymers that may be used as phase-change materials, they can also be used for PCM encapsulation, and shape stabilization.[17]

To prevent the coating or shell from leaking, PCM is encapsulated. Encapsulation increases the heat conductivity of the substance there by improving the material's performance. Encapsulation is classified into three types: nano-encapsulation, micro-encapsulation, and macro-encapsulation. Nano-encapsulation involves particle sizes that range from 1 to 1000 nm. [18]prepared and tested three different nano-PCMs, which include silica nano capsules, silver-coated nano PCMs and polydopamine modified nano-PCMs. [19] prepared nano-encapsulated organic PCM which was created by encapsulation of n-octadecane as a core with St (styrene) – MMA (methylmethacrylate) copolymer shell using mini emulsion in-situ polymerization method. Microencapsulation is another popular and effective method for PCM inclusion. This approach prevents PCM leakage during the meltdown phase and increases heat conductivity for improved performance during freezing/melting cycles. Macro-encapsulation includes particles that are bigger than 1 mm. Macro-encapsulation creates a protective covering and which protect the material from reduces environmental impact. Because of the microencapsulation, the PCM sometimes becomes harder at the boundary of the shell while the central component becomes liquid, hence lowering the rate of effective heat transmission. created encapsulation for concentrating solar power systems using PCM NaNO3 and eutectic NaCl MgCl2 as the centre and stainless steel as the shell material [20]. The cylindrical storage vessel with the help of copper tubes that were filled with honey and paraffin oils. Hybrid PCMs includes combination of two or more PCM materials, enhancing their thermal properties [21]. The thermal efficiency of the solar collector and drying chamber with multiple PCMs increased by 43% and 25.5%, correspondingly, as compared to a traditional solar dryer [22].

In Nanotechnology-based PCM nanoparticles are introduced into the PCM to boost the thermal characteristics and stability [23]. A novel kind of PCM is formed by suspending tiny amounts of $ZnO/\alpha\text{-}Fe_2O_3$ nanocrystals in melting paraffin. Adding 1.0 wt% AS-ZnO/α-Fe2O3 nanocrystals to nanofluid-PCM improved performance by 93% and resulted in a heat gain of 47 kJ. Using nanofluids as PCMs can enhance the efficiency of solar collectors. Graphene-enhanced PCM is a sophisticated technique that uses graphene to boost the thermal conductivity and stability of the material. [24]The designed system has the ability to cut drying time by 4 hours and 555.06 liters of diesel fuel each year, and save 5604 kWh of energy and reduce carbon dioxide emissions by 5.49 tons, demonstrating the design's ecological sustainability.

The study found that the phase-change material solar dryer (PCMBSD) has a 40% more serious effect on human health and a 37.04% greater effect on the ecosystem than the cylindrical solar-assisted dryer (CSAD). In terms of resources (Rs.), the CSAD outperforms the PCMBSD by 14.18% [25]. The study also revealed that the CSAD demonstrated a much lower environmental effect than the PCMBSD. As a result, the CSAD is preferable for drying crops since it is less expensive and has a lower environmental risk. Solar drying systems, whether they rely purely on solar power or are self-controlled hybrid drying systems, they significantly reduce carbon dioxide emissions by reducing the amount of energy used. In reality, the proportion of fuel consumption savings varies depending on the kind of solar dryer system used. Benefits could vary from 20-40% in hybrid systems to 100% fuel elimination in natural ventilation Greenhouse Solar Dryer [26].

6. POLICY AND SUPPORT

Solar drying may not be widely adopted without government support because of obstacles related to cost, technology, and awareness. However, despite the obvious advantages, solar drying technologies have not been widely adopted, especially by small and marginal farmers. Here, government policies are essential for encouraging the use of solar drying, promoting sustainable farming, and advancing more general national development objectives. Governments can increase the adoption of solar drying technology by offering financial incentives, technical support, and innovation encouragement.

The Indian government has implemented various support measures and policies to promote solar drying as part of its broader initiatives for renewable energy and sustainable agriculture. Here are some key aspects:

- National Solar Mission
- Integrated Solar Dryer and Pyrolysis pilot plant
- Subsidies and Financial Assistance:
    - Pradhan Mantri Kisan Samman Nidhi (PM-KISAN)
    - Indian government subsidies exist through the National Horticulture Board for Hoop house tunnel dryers (HTDs)
    - Installation of Solar Drying Units
- Research and Development
- Capacity Building and Training Programs
- Promotion of Farmer Producer Organizations (FPOs)
- Market Support
- Climate Resilience Initiatives

CONCLUSION

These initiatives reflect the Indian government's commitment to harnessing renewable energy and supporting sustainable agricultural practices, ultimately contributing to food security and rural development. Government does not invest enough in solar energy initiatives, which leads to lack of subsidies, especially in areas where solar energy is less accessible. As a result, the cost of solar energy is lower, but the government policies donot attract investors. While the government strongly supports traditional energy sources which makes those energy costs lower and creates an unfair situation for solar energy. Because of this there isn’t enough demand for solar equipment like solar dryers. In many developing countries, solar projects are supported by special payments called FiTs called feed in tariffs, but these aren’t attractive enough for developers to invest. The government needs to create better policies to encourage investment in solar energy technologies.

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