Recent Advances in Solar Drying Technologies- A Short Review

Charles Berville,
Building Services Department
UTCB
Bucharest, Romania
charles.berville@phd.utcb.ro

Cristiana-Verona Croitoru,
CAMBI Research Center
CAMBI
Bucharest, Romania
cristiana.croitoru@utcb.ro

Ilinca Nastase,
CAMBI Research Center
CAMBI
Bucharest, Romania
ilinca.nastase@utcb.ro

***Abstract*— The number of previous studies on food and energy consumption is set to mark a significant growth by 2050 worldwide. In southern countries, agricultural and marine food products, such as vegetables, fruits, rice, coffee, nuts and fish require drying in order to be preserved. Drying processes are widespread in agricultural, marine and industrial sectors, from fruits and vegetables to wood and textile production. In this context, solar drying can be one of the keys to solve these issues, as it is sustainable and cheaper than conventional drying methods. In this paper, we review the latest advances in solar drying technologies, special attention is given to solar dryers with thermal energy storage. Furthermore, the environmental aspects and environmental assessment methodologies concerning the use of solar dryers are discussed.**

***Index Terms*- Solar dryers, Phase Change Materials, Air Solar Collectors, Energy efficiency, Environmental performance.**

I. Introduction

Drying processes are widespread in agricultural, marine and industrial sectors, from fruits and vegetables to wood and textile production. In southern countries, agricultural and marine food products, such as vegetables, fruits, rice, coffee, nuts and fish require drying in order to be preserved. Solar radiation is used from centuries for the drying of agricultural products, it all began with open sun drying and, in last decades, more efficient solar dryers were developed. However, solar dryers are still not widespread nor widely used, mostly due to their intermittence and average yield. Since the industrial age, dryers using fossil fuel, wood or electricity are more widespread, because of their continuous power and yield. Nevertheless, the number of previous studies on world food and energy consumption is set to mark a significant growth by 2050. In this context, closely linked to the fight against global warming, solar drying can be one of the keys to solve these issues, as it is sustainable, energy efficient, cheaper than conventional drying methods using fossil energies and independent of energy networks. In this paper, we review the different types of solar dryer from the simplest open sun drying to most complex solar drying systems. Special attention is given to solar dryers incorporating thermal storage materials, such as phase change materials (PCM), to mitigate the intermittent nature of the solar energy. Furthermore, the environmental aspects and environmental assessment methodologies concerning the use of solar dryers are discussed.

II. Types of Solar Dryers

In the literature, many kinds of solar dryers have been developed, from cabinet type solar dryers to indirect type solar dryers. Sharma et al. [1] provided an exhaustive review of the wide diversity of drying systems based on solar energy approaching details of construction and working principles from easy-to-fabricate dryers to complex dryers. Figure 1 presents a general classification of solar drying systems given by Ekechukwu and Norton [2]. Ekechukwu and Norton realized a complete review of solar drying principles, technologies and applications in three volumes. Solar dryers are generally categorized following their heating mode into two main groups: natural convection dryers, also called passive dryers or passive solar-energy drying systems; and forced convection dryers, also called active dryers or active solar-energy drying systems. Then, each group is separated into three sub-categories: direct-type solar dryers; indirect-type solar dryers; and mixed-mode solar dryers. Direct-type solar dryers usually consist of an integral chamber made of transparent materials such as glass and opaque materials such as wood. In this category of solar drying system, the sun is directly radiating on the products, so the products absorb the direct sunlight, hence the name “Direct solar dryer”. In the literature, one of the first design of solar dryer was a direct solar dryer filed in America by Stanley K. Everitt in 1976 and

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patented in 1980 [3], it was described as "a box-shaped made of black walls and covered by a transparent material". Indirect-type solar dryers are generally made of two pieces, an air solar collector combined with a drying chamber. This kind of solar dryer was thinking to avoid the direct radiation, which can deteriorate the drying product. At last, mixed-mode solar dryers combined the two modes by using an air solar collector to pre-heat the air and by using transparent material for the drying chamber in order to reduce the drying time.

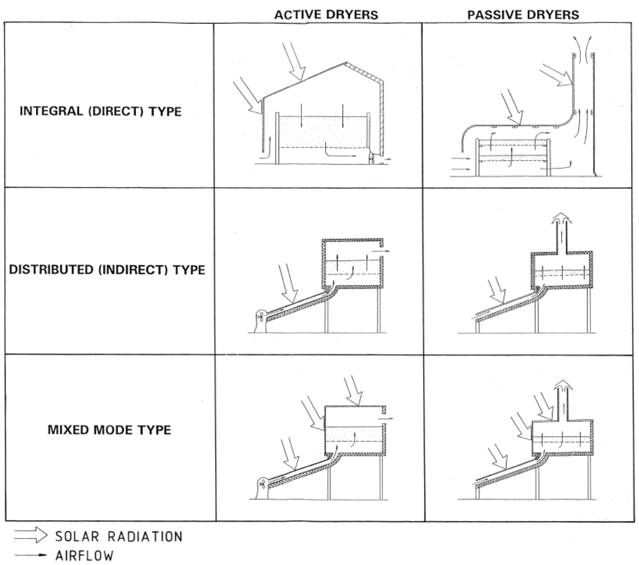

Figure 1: Classification of solar dryer designs

III. Recent Advances

In recent studies, there was considerable emphasis placed on solar dryers using solar air collectors and on ways of improving their cost and thermal efficiency.

A. *Enhancement of solar dryers*

Research and development work were conducted on solar dryers incorporating thermal storage materials, such as phase change materials (PCM), to mitigate the intermittent nature of the solar energy. Shalaby et al. reviewed various solar dryers using phase change materials as energy storage means. Overall, it is concluded that increasing the PCM's latent heat and the surface area of the PCM container improve the thermal efficiency of solar dryers in addition to provide a more constant drying. Shalaby and Bek have carried out an experimental work on the optimization of solar dryers with the use of energy storage materials. They developed an innovative indirect solar dryer incorporating PCM as energy storage means, the novel solar dryer was tested with and without PCMs, results have shown that using PCMs increase the drying air temperature by 2.5 -7.5°C after sunshine hours for about five hours and maintains the drying air temperature at constant value for 7 consecutive hours a day. The main innovation of this indirect solar dryer is the location of the PCM storage unit at the inner bottom of the drying chamber to avoid heat losses to the environment. El Khadraoui et al. [4] introduced a novel designed of forced convection indirect solar dryer incorporating paraffin wax (PCM) as energy storage medium. The solar dryer is composed of two glazed air solar collectors (with and without PCM) and a drying chamber. The absorber plate of the solar collector consists of an aluminum cavity filled to 80% with 60kg of paraffin wax. The solar air collector was used during the daytime and the air solar collector with PCM was used during the night-time. In this study the use of PCM in the air solar collector helped to increase the drying temperature by 4 to 16°C above the ambient temperature and to reduce the relative humidity by 17 to 34.5% below the ambient relative humidity during the night-time. In addition, the daily energy and exergy efficiency of the air solar collector with PCM reached 33.9% and 8.5% respectively. Jain et al. developed a natural convective solar dryer, combining two air solar collectors, one in the lower part of the drying cabinet to heat the drying air and the other one above the drying cabinet to create a natural draft system. To maintain a drying continuity, a packed bed thermal energy storage with a 50kg PCM capacity has been attached to the drying chamber. The packed bed thermal storage consists of 48 tubes filled with paraffin wax placed in zigzag. This solar dryer can be effectively operative for 5-6h after sunshine hours while providing a drying temperature 6°C higher than the surrounding air.

PCM encapsulation geometry, material and placement is a key factor to optimize heat transfer and air flow inside solar dryer systems. Research was conducted to determine the influence of the PCM macro or micro encapsulation geometry on the system efficiency. Raj, Srinivas et al. [5] made use of a double-pass solar collector for applications in drying processes to investigate the influence of cylindrical and rectangular PCM metallic containers on heat storage and recovery. They observed that PCM stored in cylindrical encapsulate has better stored heat retrieval than in rectangular encapsulate, with an average efficiency of 67% and 47.2%, respectively. Thus, cylindrical encapsulates are more beneficial for energy storage on short period, at 6:30, at the end of the discharging cycle the recorded PCM temperature was 44.4°C for rectangular encapsulates and 30.1°C for cylindrical encapsulates.

Studies on solar dryer with PCM have shown that PCMs can mitigate transients time when the outlet air is too cold or too hot by maintaining an optimal temperature. However, one of the major drawbacks of PCMs is their low thermal conductivity, several methods to improve latent heat storage components have been studied, such as the introduction of high thermal conductivity materials into the heat storage medium. Reyes et al. [6] outlined a solar dryer with an innovative thermal energy storage system. Indeed, they used recycled soft drinks cans to store a phase change material (paraffin wax) into a solar energy accumulator, and in order to boost the thermal conductivity of the paraffin wax they placed aluminum stripes made of recycled cans into the cans filled of paraffin wax. Results have shown that the mixture combining 5% aluminum wool with paraffin wax doubled the thermal conductivity of the paraffin wax. In another study, Vasquez, Reyes et al. modelized the precedent solar dryer using a mathematical model separated in three stages for the three major components of the system, namely, the drying cabinet, the solar energy accumulator and the solar panel. The model predicts the air and product characteristics, such as temperature, humidity and moisture. It also predicts the thermal behavior of the solar accumulator during the energy discharge and charge stages. The fit of the regression model was evaluated using R^2 and Root Mean Square Error (RMSE). Numerical simulation results have shown that the solar accumulator can heat the air using for the drying for a duration of 4 to 8 hours during off-sunshine periods. A.H. Abed [7] carried out an experimental examination on the improvement of the thermal storage efficiency of a solar air heater combining sensible heat storage components and PCMs in cylindrical capsules. Results have shown that the optimal compound providing the highest thermal storage duration over the discharging process is 80% pure sand with 20% paraffin wax, this compound leads to increase the outlet air temperature by 9.2% compared to pure sand.

Solar dryers are not only used for fruits and vegetables drying but also wood, textile and desalination processes. In the sphere of humidification–dehumidification desalination solar air heaters are rarely investigated in comparison with solar water-based heaters, despite this, in recent years promising studies have been conducted on solar air heaters for humidification–dehumidification (HDH) desalination. HDH desalinization is a usual procedure adopted for the generation of distillate water. Narayan et al. provided a paper presenting the potential of solar-driven HDH desalination and concluded that this technology holds considerable promise for water production applications especially for decentralized and small-scale applications for developing countries, this system being cheaper and greener than conventional desalination technologies. Summers et al. [8] invented and constructed a solar air collector with incorporated phase change materials in order to afford a constant temperature as long as possible for humidification–dehumidification desalination. They used mathematical model to find the optimal PCM layer thickness placed under the absorber plate, results have shown that a PCM module of 8cm thickness gives the most constant temperature for the smallest quantity of PCM. They implemented several optimizations to intensify the thermal conductivity and stability of the paraffin wax, such as an aluminum matrix embedded in the storage and an optimized metal surface roughness. Summers et al. concluded that their system is promising but it remains expensive for a large-scales projects. In order to achieve a comprehensive and efficient system Kabeel et Abdelgaied [9] made use of an indirect solar dryer consisting of two stages to produce distillate water and drying products. In addition to the generation of both distillate water and dryed products, experimental results have shown an enhancement of the moisture removal when reheating with the second stage of the dryer by 71.78% compared to one-stage drying unit.

Nowadays, to upgrade the performance of solar drying systems it is highly recommended to use numerical simulation such as CFD simulation. Abhay L. et al. [10] performed 2D numerical simulations to enhance the heat transfer and air flow in a solar air collector by providing artificial roughness on the absorber plate surface. Results have shown that roughened absorber plate with square-shaped rib enhances the heat transfer by 3.54 times. Roughness elements in a solar air collector is a frequent research topic, in a similar study, Singh et al. inspected a solar air heater duct with roughness elements and found a maximum augmentation in Nusselt number and friction factor of 2.14 times and 3.55 times respectively above the smoother duct.

B. Desiccant thermal storage

The use of desiccant thermal storage in solar dryer systems presents special attention because of two major advantages, a high latent storage density and a natural process of moisture removal. Ndukwu, Bennamoun et al. [11] achieved energy and exergy assessments on a natural-convective solar-dryer integrated with desiccant thermal storage. They evaluated the potential of the sodium sulphate decahydrate ($Na2SO4\cdot 10H2O$) more widespread under the name of Glauber's salt and sodium chloride (NaCl) used as phase change materials. $Na2SO4\cdot 10H2O$ pellets and NaCl were integrated in a stainless storage. In order to diminish the heat losses from the energy storage module to the ambient air, the thermal energy storage was settled in the solar collector during sunshine hours and moved in the drying chamber during nighttime, this strategy is used in similar studies to boost the energy efficiency of the solar dryer. Results have shown that during nighttime $Na2SO4\cdot 10H2O$ helped to maintain much lower humidity in the drying cabinet compared to NaCl. The drying process required 24.5, 36.5 and 40.5 sunshine hours to diminish the moisture content of the product (red chili) from 72,24% to 7.6%, 10.1% and 10.3% respectively with $Na2SO4\cdot 10H2O$ storage, NaCl storage and without storage.

C. Transpired solar collectors

Few researches were conducted on the potentiality of Unglazed Transpired Solar Collectors (UTSC) for applications in solar drying. Transpired Solar Collectors have been widely employed for pre-heating fresh air and heating spaces, but still rarely implemented in solar drying systems. However, a study [12] conducted by Bandara et al. has shown that Unglazed Transpired Solar Collectors have a promising future in solar drying, they observed similar efficiency between unglazed and glazed solar collector under the same conditions, 38,41% respectively 30,04%. Results have also shown no difference for the outlet temperature between glazed an unglazed solar collector, 45,7°C and respectively 45,5°C. Unglazed Transpired Solar Collectors being cheaper than glazed solar collectors they offer very promising alternative for solar drying technologies.

D. *Hybrid solar dryers*

Solar dryers have the drawback of their reliance on the non-constant solar energy, therefore like many systems based on renewable energies solar dryers have a hybrid version for an operating consistency. Hybrid or assisted solar dryer are solar drying systems combining solar energy with an auxiliary source of energy, such as conventional fuel systems. Hybrid solar dryer are mostly used for large scale installation or for specific sectors such as fishery. Innovative technologies combining solar dryers with infrared waves systems have emerged in recent studies. Ziaforoughi and Esfahani [13] developed a combined solar and intermittent infrared waves dryer system. The scope of this study was to compare an indirect solar-assisted intermittent infrared dryer to a simple intermittent infrared dryer. This study has shown that the use of indirect solar-assisted intermittent infrared dryer reduces electrical energy consumption by 40%-69% and reduces drying time by 31% to 52% compared to the infrared dryer. Using this assisted dryer also leads to reduce the drying time in comparison with current solar dryer. There are still few articles in the literature approaching the consequences of the infrared waves assistance for solar dryers. While this is much discussed and validated for the assistance of simple hot air heater dryer, such as Hebbar et al. demonstrated in a study [14]. They have shown that combining infrared and hot air heating systems for drying applications improve the energy efficiency of the dryer, it has been evaluated to be 38%. The performance assessments revealed that this combined system helped to cut down the energy consumption by 63% and the drying time by 48% when comparing with hot air heating for the drying of vegetables (potato and carrot) at 80°C. The combination of drying, infrared and hot air heating respectively, also contributed to better results compared to infrared heating alone. These conclusive results open the way for future works on hybrid dryers combining different drying methods based on renewable energies.

IV. Environmental performance

Studies on solar dryers approaching environmental assessments are usually focused on the energy consumption and the carbon dioxide (CO_2) emissions of the system. Reduction of energy consumption and CO_2 emissions being two major advantages of solar drying systems. Lamrani et al. [15] conducted environmental and energy analysis of an indirect hybrid solar dryer using TRNSYS, results revealed that using their solar dryer for wood drying applications prevents the emission of 34% of CO_2 per year.

Environmental assessments are still less carried out when solar drying systems are examined and when performed, they are not extensive, considering only the energy used during the running time of the system, without considering the energy consumed during the full life of the product, from cradle to grave or cradle to cradle. In future study, all phases of the system life should be analyzed from raw materials to manufacturing, packaging, distribution, use and disposal, based on detailed assessments such as well-known Life Cycle Assessments (LCA).

V. Conclusions and Future Works

This review has shown that in many studies the efficiency of solar drying systems can be enhanced by improving the air solar collector performances. Solar dryers incorporating with thermal energy storage materials is a much-discussed topic in recent studies to increase the thermal efficiency of solar dryers and to reduce the energy consumption of the auxiliary system using electricity or conventional fuels. However, the chemical stability of thermal energy storage materials should be finely investigated in order to be compatible with the drying system. Moreover, it could be considered to study the potential of cascaded thermal energy storages to increase the continuity of the temperature on longer period, to mitigate the off-sunshine hours and to improve the quality of the drying.

It is also suggested to use numerical model, such as CFD simulation, to optimize the solar dryer's performance, an application can be to find optimal shapes for thermal energy storage material containers integrated in the air solar collector. We also revealed the lack of environmental impact assessment studies for solar drying applications; this can be explained by the need of a significant amount of environmental data, which are often complicated to collect.

The paper offers a point of view for understanding the actual requirements concerning solar drying researches. The findings presented above, namely integration of thermal energy storage materials, conception of numerical study and environmental impact assessment are recommended guidelines for future works on solar drying systems. These guidelines are nowadays essential to develop more sustainable and efficient drying systems in order to be compatible with future international and European energy and environmental standards.

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References

1. Sharma, A., C.R. Chen, and N. Vu Lan, *Solar-energy drying systems: A review.* Renewable and Sustainable Energy Reviews, 2009. **13**(6): p. 1185-1210.
2. Ekechukwu, O.V. and B. Norton, *Review of solar-energy drying systems II: an overview of solar drying technology.* Energy Conversion and Management, 1999. **40**(6): p. 615-655.
3. Everitt, S.K., *SOLAR FOOD DRYER.* United States Patent 4 221 059, Sep. 9, 1980.
4. El Khadraoui, A., et al., *Thermal behavior of indirect solar dryer: Nocturnal usage of solar air collector with PCM.* Journal of Cleaner Production, 2017. **148**: p. 37-48.
5. Raj, A.K., M. Srinivas, and S. Jayaraj, *A cost-effective method to improve the performance of solar air heaters using discrete macro-encapsulated PCM capsules for drying applications.* Applied Thermal Engineering, 2019. **146**: p. 910-920.

6. Reyes, A., et al., *Design and evaluation of a heat exchanger that uses paraffin wax and recycled materials as solar energy accumulator*. Energy Conversion and Management, 2014. **88**: p. 391-398.

7. Abed, A., *Thermal Storage Efficiency Enhancement for Solar Air Heater Using a Combined SHSm and PCM Cylindrical Capsules System: Experimental Investigation*. 2016.

8. Summers, E.K., M.A. Antar, and J.H. Lienhard, *Design and optimization of an air heating solar collector with integrated phase change material energy storage for use in humidification–dehumidification desalination.* Solar Energy, 2012. **86**(11): p. 3417-3429.

9. Kabeel, A.E. and M. Abdelgaied, *Experimental evaluation of a two-stage indirect solar dryer with reheating coupled with HDH desalination system for remote areas.* Desalination, 2018. **425**: p. 22-29.

10. Abhay, L., V.P. Chandramohan, and V.R.K. Raju, *Numerical analysis on solar air collector provided with artificial square shaped roughness for indirect type solar dryer.* Journal of Cleaner Production, 2018. **190**: p. 353-367.

11. Ndukwu, M.C., et al., *Energy and exergy analysis of a solar dryer integrated with sodium sulfate decahydrate and sodium chloride as thermal storage medium.* Renewable Energy, 2017. **113**: p. 1182-1192.

12. Bandara, W., B.K. Amarasekara, and C.P. Rupasinghe, *Assessment of the possibility of unglazed transpired type solar collector to be used for drying purposes: a comparative assessment of efficiency of unglazed transpired type solar collector with glazed type solar collector.* Procedia Engineering, 2018. **212**: p. 1295-1302.

13. Ziaforoughi, A. and J.A. Esfahani, *A salient reduction of energy consumption and drying time in a novel PV-solar collector-assisted intermittent infrared dryer.* Solar Energy, 2016. **136**: p. 428-436.

14. Hebbar, H.U., K.H. Vishwanathan, and M.N. Ramesh, *Development of combined infrared and hot air dryer for vegetables.* Journal of Food Engineering, 2004. **65**(4): p. 557-563.

15. Lamrani, B., A. Khouya, and A. Draoui, *Energy and environmental analysis of an indirect hybrid solar dryer of wood using TRNSYS software.* Solar Energy, 2019. **183**: p. 132-145.