SOLAR DRYING AS AN ALTERNATIVE FOR THE THERMAL TREATMENT OF AGRO-INDUSTRIAL WASTE

SECAGEM SOLAR COMO ALTERNATIVA PARA O TRATAMENTO TÉRMICO DE RESÍDUOS AGROINDUSTRIAIS

EL SECADO SOLAR COMO ALTERNATIVA PARA EL TRATAMIENTO TÉRMICO DE RESIDUOS AGROINDUSTRIALES

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ABSTRACT

Science and technology have demonstrated that it is possible to minimize the environmental impacts of solid waste generation and, at the same time, increase the supply of energy from renewable sources through the use of agro-industrial residues as biomass. Brazil is one of the countries with the greatest prospects in the world for utilizing agro-industrial residues for bioenergy, given its extensive agricultural activity. This residue, on the other hand, requires drying to be standardized and stabilized under appropriate conditions for thermochemical conversion processes to be economically and energetically viable. Thus, a significant reduction in waste moisture can be seen as an interesting alternative for the treatment and use of materials that would otherwise be improperly discarded and can now be seen as energy sources. However, drying is known to be an energy-intensive operation, and therefore, alternative, more energy-efficient, low-cost techniques have been the focus of study by several researchers, particularly when it comes to the use of solar energy. Drying using solar energy is an interesting way to diversify the country's energy matrix, as it uses free, clean, and renewable energy. It is worth noting that Brazil has great potential for generating photovoltaic solar energy, which motivates the use of solar dryers. This chapter presents a brief review of the literature on the thermal treatment of agro-industrial waste using solar energy, given that the use of alternative energy sources to a conventional drying system is of great scientific and technological relevance. The chapter concludes that the use of solar dryers for the thermal treatment of this waste may be very promising; however, studies in this vast area of research are still lacking, particularly regarding scaling up and reducing drying time.

Keywords: Biomass. Solar Energy. Renewable Energy. Drying. Particulate Systems.

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RESUMO

A ciência e a tecnologia tem demonstrado positivamente que é possível minimizar os impactos ambientais ocasionados pela geração de resíduos sólidos e, ao mesmo tempo, aumentar a oferta de energia proveniente de fontes renováveis a partir do uso de resíduos agroindustriais como biomassa. O Brasil é um dos países com maiores perspectivas no mundo de utilização de resíduo agroindustrial para bioenergia, tendo em vista sua extensa atividade agrícola. Estes resíduos, por outro lado, necessitam de secagem para que sejam padronizados e estabilizados em condições apropriadas para que os processos de conversão termoquímica sejam viáveis economicamente e energeticamente. Dessa forma, uma redução significativa de umidade dos resíduos pode ser entendida como uma alternativa interessante ao tratamento e ao aproveitamento de materiais que a princípio seriam descartados de maneira incorreta e agora podem ser vistos como fontes geradoras de energia. No entanto, a secagem é conhecida como uma operação de elevado consumo energético e, desta forma, técnicas alternativas energeticamente mais eficientes e de baixo custo de operação tem sido o foco de estudo de diversos pesquisadores, principalmente quando se trata da utilização de energia solar. Secagem empregando energia solar é uma forma interessante de diversificar a matriz energética do país, pois utiliza energia gratuita, limpa e renovável. Cabe ressaltar que o território brasileiro apresenta um grande potencial para a geração de energia solar fotovoltaica, o que motiva o uso de secadores do tipo solar. Neste capítulo é apresentada uma breve revisão de trabalhos da literatura sobre o tratamento térmico de resíduos agroindustriais a partir do uso de energia solar, visto que a utilização de métodos alternativos de fontes de energia a um sistema convencional de secagem é de grande relevância científica e tecnológica. No final do capítulo conclui-se que a utilização de secador solar para o tratamento térmico de destes resíduos pode ser muito promissor, entretanto, ainda carece de estudos nesta área tão vasta de pesquisa, principalmente no que se referente à ampliação de escala e redução do tempo de secagem dos resíduos.

Palavras-chave: Biomassa. Energia Solar. Energia Renovável. Secagem. Sistemas Particulados.

RESUMEN

La ciencia y la tecnología han demostrado positivamente que es posible minimizar los impactos ambientales provocados por la generación de residuos sólidos y, al mismo tiempo, incrementar la oferta de energía proveniente de fuentes renovables mediante el aprovechamiento de residuos agroindustriales como biomasa. Brasil es uno de los países con mayor perspectiva del mundo en el aprovechamiento de residuos agroindustriales para bioenergía, dada su extensa actividad agrícola. Estos residuos, por otra parte, requieren de un secado para poder estandarizarlos y estabilizarlos en condiciones adecuadas para que los procesos de conversión termoquímica sean económica y energéticamente viables. De esta forma, una reducción significativa de la humedad de los residuos puede entenderse como una alternativa interesante al tratamiento y aprovechamiento de materiales que inicialmente serían desechados de forma incorrecta y que ahora pueden ser vistos como fuentes generadoras de energía. Sin embargo, el secado se conoce como una operación de alto consumo energético y, por lo tanto, técnicas de operación alternativas, más eficientes energéticamente y de menor costo han sido foco de estudio por parte de varios investigadores, especialmente cuando se trata del uso de energía solar. El secado con energía solar es una forma interesante de diversificar la matriz energética del país, ya que utiliza energía gratuita, limpia y renovable. Cabe destacar que el territorio brasileño tiene gran potencial para la generación de energía solar fotovoltaica, lo que motiva el uso de secadores solares. En este capítulo se presenta una breve revisión de la literatura sobre el tratamiento térmico de residuos agroindustriales utilizando energía solar, ya que el uso de fuentes energéticas alternativas a un sistema de secado convencional es de gran relevancia científica y tecnológica. Al final del capítulo se concluye que el uso de un secador solar para el tratamiento térmico de estos residuos puede ser muy prometedor; Sin embargo, aún faltan estudios en esta vasta área de investigación, especialmente en lo que se refiere a ampliar la escala y reducir el tiempo de secado de los residuos.

Palabras clave: Biomasa. Energía Solar. Energía Renovable. El Secado. Sistemas de Partículas.

1 THE PANORAMA OF THE BRAZILIAN ENERGY MATRIX

Currently, Brazil has a growing demand for electricity due to population growth, urbanization, economic development, and extreme weather effects that cause long periods of drought. Brazil is a country that has an electricity matrix of predominantly renewable origin, with emphasis on the hydro source. According to the Energy Research Company (EPE, 2023), 64% of all domestic energy supply comes from hydroelectric plants alone, with renewable sources accounting for 88% of the domestic electricity supply. However, over the past few years, these natural reserves have had their capacities compromised due to the seasonal rainfall regime (Caldeira *et al*., 2023), known as hydrological risk (Agência Câmara de Notícias, 2019). Since a large part of the renewable source comes from hydropower, when production in hydroelectric plants is insufficient to meet population demand in times of drought, there is an increase in the cost of electricity due to the purchase of energy from other countries (ANEEL, 2022) and the activation of thermoelectric plants that use fossil fuels, such as coal, diesel oil and gas, causing a significant increase in the emission of CO2 into the atmosphere.

Even though Brazil is a country of intense agricultural activity, which places it as one of the nations with the greatest possibilities of generating renewable energy in the world from biomass from agro-industrial waste (Costa *et al*., 2022), only 8.8% of the total renewable energy generated in the country comes from other sources, such as biomass, sugarcane bagasse, rice husks, firewood and lye, a by-product of wood processing in pulp and paper mills, are the main biomasses used in the country (EPE, 2023). Sugarcane bagasse alone represents 55% of the total use of biomass in renewable energy in Brazil (EPE, 2023). This is due to the high availability of bagasse at low cost and in large quantities, given the high production capacity of sugar and alcohol mills, which corresponded to a production of approximately 32 million m3 of ethanol and 37 million tons of sugar in the 2022/2023 harvest (UNICA, 2023). Despite the surplus of electricity produced from the burning of sugarcane bagasse, there are periods of sugarcane off-season and much of the bagasse has to be stored in the yards of the industries, which are mostly concentrated in the state of São Paulo (UNICA, 2023). In addition to limiting the use of renewable energy in a given region, increased competition for bagasse can harm the supply of bioenergy when considering the long term (Costa *et al*., 2022). Parallel to the generation of sugarcane bagasse, other agro-industrial residues with high energy potential are generated in large quantities, but without its efficient use in the production of clean energy. According to the study developed by Souza *et al*. (2021), Brazil has enormous regional potential to be explored from alternative biomasses, given its intense agricultural activity favored by its tropical climate, which generates a large amount of solid waste daily. The Brazilian territory is one of the few that can collaborate with abundant renewable raw material, capable of meeting its internal goal and still helping other nations (Órigo, 2021), and a biomass production of approximately 1 GT is expected by the year 2030 (Moraes *et al*., 2017).

2 DRYING AS A HEAT PRETREATMENT OF BIOMASS

The application of biomass for bioenergy production can be approached as heat production by combustion or biogas and bio-oil production by gasification and pyrolysis, as well as biofuel production by fermentation (Havlík *et al*., 2022). In any of these treatments, especially thermal ones, the high humidity in the biomass compromises the combustion yield, thermochemical conversion, and calorific value of the raw material, in addition to resulting in an increase in handling, processing, and storage costs (Cláudio *et al*., 2022). Drying is used as a heat pretreatment step in different processing units, aiming at the efficiency of the subsequent steps (Silva *et al*., 2023), and can add value to the dry fuel, making it reusable, opening up an interesting range of possibilities for the efficiency of combined heat and power plants. It is in this case that drying is an important step in combined heat and power plants. In the thermochemical conversion of wet biomass, some of the thermal energy will be required to evaporate the water as the calorific value is reduced. As long as the biomass is pre-treated thermally using drying, the efficiency of the thermochemical conversion increases, since the energy demand for moisture removal decreases (Pang, 2015). In addition to improving the conversion efficiency and quality of the bioenergetic product, the drying process also has some interesting advantages, such as dry fuel with greater durability, minimization of the risk of fire and explosions, reduction of pollutants and emissions (Alamia *et al*., 2015), improvement of the product's gas quality (Brammer and Bridgwater, 2002) and prevention of organic matter loss (Haarlemmer, 2015).

As much as there are significant benefits of drying biomass before thermochemical conversion, it is worth noting that drying can consume up to 80% of the cost of biomass pretreatment (Aljabri et al., 2023). According to Kudra (2004), due to the latent heat of vaporization provided for the removal of moisture, drying is probably the industrial process with the highest energy consumption. The energy cost in terms of heat represents a significant amount in the total cost of drying, especially in the case of conventional convective dryers (Kudra, 2012). The search for more energy-efficient drying processes with low operating costs has been the focus of study by several researchers, however, due to the complexity involved in drying processes, it is still a challenge.

3 BIOMASS DRYING TECHNIQUES

Different biomass drying techniques for integrated bioenergy plants were presented by Pang (2015), including conveyor-type mobile bed dryer, rotary dryer, fluidized bed dryer and pneumatic dryer (*flash*). In a more recent study, Yi *et al*. (2019) highlighted the same dryers as the most conventional ones applied to biomass drying in bioenergy plants. In general, the rotary dryer is the most suitable for drying agro-industrial waste in general due to its flexibility and versatility in handling heterogeneous and difficult-to-flow materials, which is one of the main characteristics of agro-industrial waste (Sousa and Ferreira, 2019). One of the main advantages of using rotary dryers is that this type of dryer handles non-uniform solid particles (Dalele *et al*. ,2015). However, according to Pang (2015), the main disadvantage is the risk of fire at temperatures above 250 °C, but it can be circumvented with the concurrent flow configuration.

Traditional dryers use air heating from electrical resistances or the burning of fuels such as LPG or firewood, depending on their operational capacity. In view of the problems of the use of fossil fuels and the increasingly significant consumption of energy that the world is currently experiencing, there is an urgent need to replace conventional energy sources with renewable energies. Such urgency is mainly motivated by the need to reduce the energy and fuel consumption of conventional dryers when they are characterized by low thermal and energy efficiency. Thus, the study of more efficient drying techniques and alternative to conventional dryers is of interest from an environmental and technological point of view.

4 DRYING USING SOLAR ENERGY

The drying process using solar energy occurs due to the exposure of the material to radiation directly or indirectly. This technique promotes drying at significantly lower costs than conventional drying, considering that the solar energy used to heat the drying air has no costs (Purohit et al., 2006). In addition, this technique allows obtaining products with the desired final quality and with minimal environmental impact (Bennamoun and Li, 2018). From an economic and environmental point of view, solar energy is an interesting way to diversify the country's energy matrix, providing a process using clean, renewable and free energy.

An important aspect that deserves to be highlighted is that Brazil has great potential for photovoltaic solar energy generation. The average solar irradiation potential in the Brazilian territory varies between 3.6 and 6.3kWh/m2.day, even the region with the lowest average solar irradiation in the country, has more potential for the use of sunlight in the generation of clean and renewable electricity than leading countries in the sector, such as

Germany or Japan (ABSOLAR, 2024). The characteristics of this process have made the study of drying using solar dryers intensified over the years.

Das *et al*. (2021) analyzed the drying of a hybrid solar food dryer with air heating using a solar collector. An average thermal efficiency of 24% was obtained, which was within the margin for solar dryers. On the other hand, the air inlet temperature varied considerably during the experiments, with the efficiency reduced to 15.9% at the end of the drying with the reduction of solar incidence in this period. In order to ensure uniform drying and constant efficiency, Matapour *et al*. (2024) introduced a thermal energy storage material (paraffin) in the solar collector coupled to a bench-scale rotary dryer. The authors achieved an average thermal efficiency of 58.68% and drying for a time beyond the solar period, however, the control of the air inlet temperature still seems to be a problem to be overcome. Iranmanesh *et al*. (2020) found that the heating of the drying air using heat exchangers operating with heated water from solar concentrators ensured the control of the air temperature, being more interesting than the drying systems that operate only with solar collectors. However, it was not possible to obtain an air inlet temperature higher than 50 °C, which can considerably increase the drying time for materials whose process is limited by moisture diffusion. Silva *et al*. (2020) developed an energy and exergy analysis of the corn drying process in a hybrid dryer coupled to a photovoltaic system. The photovoltaic system was used to power an electric heater and fans and also to preheat the drying air through the use of the back of the photovoltaic panel as a heat exchanger, increasing the air temperature before the solar collector entered. The results showed an exergy efficiency ranging from 22.2 to 45%, indicating the energy viability of solar drying.

5 DRYING OF AGRO-INDUSTRIAL WASTE IN SOLAR DRYERS

Rodrigues et al. (2015) evaluated the use of a natural convection solar dryer and a solar dryer bioreactor with forced air circulation for drying cashew residues enriched with 2% yeast of the species Saccharomyces cerevisiae. The authors reported that both types of dryers did not present sufficient performance to reduce the humidity of the samples by up to 12% b.u., however, the solar dryer bioreactor presented better performance for the operating conditions presented. To obtain lower moisture values of the residue, the authors suggested interrupting the drying process around 3:30 p.m., a period in which solar activity decreases and increases the relative humidity of the air, and restarting the drying process the next day.

Arantes et al. (2019) evaluated the efficiency of a mixed passive solar dryer applied in the drying of the outer sheath of peach palm. These residues come from the heart of palm production industries and are generated in large quantities, since the heart of palm sold represents only 30% of the volume that is harvested in the field, while the rest is discarded. In addition, the outer sheath of peach palm has high humidity, around 85% b.u. Information such as meteorological conditions, relative humidity, temperature of the drying chamber and humidity on a wet basis of the waste throughout the drying process were collected. The authors reported that to achieve the reduction of the average moisture content of the residues from 85 % to 22 %, it took 38 days. As a way to reduce drying time, it has been suggested to reduce the size of the batch, as well as the installation of electric fans or exhaust fans for the purpose of increasing airflow inside the dryer.

Do Nascimento et al. (2021) studied the drying of Brazil nut processing residue in layers with different thicknesses in a direct solar dryer and by direct exposure to the sun. Different mathematical models were adjusted to the experimental data and the drying rates and effective diffusivity of each experimental procedure were also determined. The authors reported that under the experimental conditions evaluated, the performance of the solar dryer for drying Brazil nut waste was satisfactory, since the solar dryer reached temperatures about 80% higher than the temperatures recorded in the environment outside the dryer. The drying rates obtained for the solar dryer were higher compared to the drying by exposure to the sun. It was also found that the Midilli model proved to be the most adequate for predicting the drying of the samples and the effective diffusion coefficients of moisture were higher in the dehydrated samples in the solar dryer compared to the drying by exposure to the sun.

Oni et al. (2021) evaluated the drying of fermented Cardaba banana peels in a solar dryer, open sun dryer and tunnel dryer. As a result, the authors found that Page's model presented the best fit for the solar drying process. Sun-dried samples had a single descending rate pattern, while solar dryer and tunnel samples exhibited a second descending rate pattern. The effective diffusivity values obtained for samples dried in solar dryer, tunnel and exposed to the sun were $2.92\times 10^{-11} m^2/s$, $1.98\times 10^{-11} m^2/s$ and $1.09\times 10^{-11} m^2/s$, respectively. The activation energy in the process was 64.9 kJ/mol.

Nunes et al. (2022) studied the use of a solar dryer for the drying process of green coconut shells for energy production purposes. It was found by the authors that the solar dryer, under the conditions submitted, presented itself as a good resource to replace the greenhouse in the drying of coconut shells, it was also verified that the solar dryer used reached internal temperatures above 70°C, even when the ambient temperature was around 30°C. Finally, the authors reported that it took 20 days for the green coconut waste to lose around 80% of its moisture.

Montero et al. (2015) investigated the drying of different types of waste from olive oil production in different solar dryer operating configurations: natural or forced convection for passive and active mode, incidence of indirect or mixed solar radiation on the product, and use of an additional energy supply system (hybrid). As main conclusions, the authors reported that the temperature of the product reached higher values when using the hybrid mode, showing the relevance of using an auxiliary energy source during night periods or periods of low solar radiation. In addition, the hybrid active mode allowed a considerable reduction in drying time, being an aspect to be considered for its use in periods of low solar radiation or at night.

Capossio et al. (2022) experimentally studied the use of a natural convection solar dryer as an alternative to a conventional convective drying system for the drying process of waste from the brewing industry. The authors mentioned that the solar dryer does not need energy from the grid to work, eliminates 100% of the CO2, equivalent, produces a dry product with quality, costs about 40 to 45% less than the conventional convective dryer. However, the drying time of malt bagasse in a solar dryer was much longer, consequently reducing the total yield. Perazzini et al. (2025) reported in their work that heat and mass transfer relied heavily on climate change. The heat and mass transfer model proposed by the authors showed good agreement between the measured and estimated data. The estimated heat transfer and mass coefficients ranged from 10.95 to 35.11 W m^{-2}°C^{-1} and 0.000159 to 0.000656 kg m^{-2} s^{-1}, respectively.

Lee et al. (2024) evaluated the characteristics of solar drying of sugarcane bagasse. It took nine days for the average moisture content of sugarcane bagasse to be reduced from approximately 47% b.u. to 9% b.u. The authors estimated that 27% of the total solar radiation collected was used to evaporate water from sugarcane bagasse. Gurmesa et al. (2021) also reported that solar energy was adequate for the drying of bagasse pulp, during the solar drying period, the maximum drying temperature obtained was 52 °C.

Several of the studies cited report the long time required to dry agro-industrial waste in a solar dryer. The solar drying of this type of waste is still a major challenge, in view of the wide variety of existing agro-industrial residues that have intrinsic characteristics of each material, as well as the high humidity of the waste, the diversity of types of solar dryers, the influence of climatic conditions and drying time, which are still limiting factors for the expansion of the scale of this technique. Thus, the study of the drying of agro-industrial waste in a solar dryer is of interest to science and technology not only for the application of an equipment of wide importance in the literature, but mainly for the possibility of developing and using alternative systems to conventional drying systems that can be applied in industrial processes in the future.

6 FINAL CONSIDERATIONS

Currently, drying has been used as a thermal treatment of solid waste of different characteristics with the purpose of generating a dry material so that it can be used as a by-product, avoiding its simple disposal in the environment. Different types of dryers can be employed in the drying process, the most commonly employed being the rotary dryer, conveyor and flash. It should be noted that, despite the versatility of conventional dryers for drying solid waste, the drying process can require a large amount of energy and fuel, favoring emissions of polluting gases and high operating costs. In addition, one of the great challenges of drying agro-industrial waste is related to the intrinsic physical, chemical and biological characteristics of each solid waste that make the study of drying a challenge and, at the same time, promising.

Solar drying is an operation that has been studied and has achieved positive results, which may make it a technology on the rise. Despite the considerable number of studies found in the literature, the thermal treatment of solid waste using solar energy can be considered a challenge, since there is still a great diversity of solid waste to be studied and a great diversity of systems available.

In general, this chapter has an introductory character, presenting a brief review of the works published in the literature in this broad area of research that is the solar drying of agro-industrial waste. This theme still needs further studies and, mainly, studies related to the expansion of scale and reduction of the drying time of agro-industrial residues using a solar dryer.

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