SOLAR DRYING - A TECHNOLOGY FOR SUSTAINABLE AGRICULTURE AND FOOD PRODUCTION

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Summary

Drying, particularly of crops, is an important human activity and globally the use of dried products is widespread. For preservation, quality improvement and processing purposes, moisture must often be removed from both organic and inorganic materials. Sun drying and mechanical dehydration using fossil fuels are the most common technologies used. Sun drying is a low-cost drying method but the final quality is variable, while mechanical dehydration is an energy intensive process and contributes substantially to energy use and greenhouse gas emissions.

Many products, however, must be dried at relatively low temperatures, i.e., less than 100 ^{0}C to ensure the desired product quality and solar dryers can often be used instead of sun drying or conventional dehydration systems. There are three main types of solar dryer (direct, indirect and mixed modes) but these classifications can be further sub-divided depending on the type of heat transfer fluid, the direction and the source of the flow, and the inclusion of thermal storage and a supplementary energy system. In practice, however, some types of solar dryer have proven to be more feasible than others.

Several ways can be used to evaluate the technical performance of solar dryers but economic and practical issues will often be more important in determining their acceptability. A solar dryer can be designed using any one of a number of

methodologies, but these are less well developed than for other solar technologies. Advances in design methods, absorber and glazing materials, and control systems will bring improvements in the technical performance of solar dryers and these will all contribute to the greater acceptance of a technology that can play an important role in a more sustainable world, particularly the food production system.

1. Introduction

The importance of dried foods cannot be overestimated. The kitchens and food stores in any country will confirm the quantity and diversity of dried foods in use. The list of foods is impressive. Grains, fruits, vegetables, spices, meat, fish, nuts and beverages such as tea and coffee are all dried and consumed in large quantities around the world.

Drying may be required for several reasons. Firstly and most often, water is removed from the fresh crop to extend its useful life. The dried product is later re-hydrated prior to use in order to produce a food closely resembling the fresh crop. Dried vegetables are an example of this drying application. Secondly, a crop may require drying so that it can be further processed. For example, many grains are dried so that they can be ground into flour. Finally, fresh crops are sometimes dried so that a new product, distinctly different from its original form, can be produced. Sultanas, the dried form of grapes, are an example of this drying application.

The importance of food drying is likely to increase. The global population is predicted to exceed eight billion by the year 2025 (Cliquet and Thienpont, 1995). Food production must therefore be increased to meet the rising demand but this is unlikely to come from simply growing crops on previously uncultivated land (Dyson, 1996). One strategy to increase food supplies is to minimize crop wastage. In developing countries alone, the minimum estimates of post-harvest losses, including those from poor drying, vary between 10-20% (Pariser, 1987). A 1978 report by the National Research Council of the National Academy of Sciences in Washington, D.C., cited by Salunkhe and Kadam (1998), puts post-harvest losses as high as 30-40% in both industrialized and developing countries.

In addition to foods for human consumption there are many other products that require drying. These include organic crops like timber and rubber and inorganic materials like paint. All of the above arguments emphasize the importance of drying in people's lives. However, according to Mujumdar (1990), "drying …. is the most energy-consuming industrial process". It requires approximately 2.4 MJ to evaporate one liter of water. To dry one metric ton of most fruits in a conventional dehydrator to the safe moisture content for long-term storage requires approximately 100 liters of oil.

The shortage of energy is an issue in many countries, particularly those in the developing world. Even where conventional energy is plentiful, there is pressure to reduce the amount of fossil fuels used. Concern over global warming is universal and this has focused our attention on energy intensive processes like drying where fossil fuels can often be replaced by renewable and non-polluting sources of energy. Drying one metric ton of fruit in a conventional dehydrator produces approximately 300 kg of carbon dioxide.

Solar energy is an obvious energy source for drying various products, particularly food crops. Many crops are harvested in the summer months and are usually dried at temperatures below 70 ^{0}C - a temperature which can be readily attained by solar technology. The growers dry many crops at the point of production themselves so there is usually adequate land area available for the solar drying system.

Some solar technologies like photovoltaic cells and water heaters have become increasingly popular, but solar dryers are less widespread in use and therefore less well understood. This article presents an overview of solar dryer types and their applications. It discusses the performance of these dryers and the other non-technical factors that influence their acceptance in both industrialized and developing countries. The methodologies used to design solar dryers are described. Initially some fundamentals of drying are presented in order to understand what solar dryers are trying to achieve and what is required when designing a solar dryer.

2. Drying Fundamentals

Drying involves the removal of moisture and, in thermal drying, this is achieved through the application of heat to the product. The heat increases the vapor pressure of the moisture in the product above that of the surrounding air. Pressure and thermal gradients cause the moisture, both liquid and vapor, to move to the surface of the product. Evaporation takes place and water vapor is transferred to the surrounding air. This air may become saturated but the process of drying continues if this moist air is replaced by less saturated air.

In a crop there is a combination of free (or unbound) and bound moisture. Free moisture is water that can move through the product in an unrestricted way. Its movement is not dependent on the internal structure of the crop. The vaporization-evaporation process is at a maximum when there is sufficient free water in the product to replace that evaporated at its surface. As this moisture is evaporated the moisture content of the product falls and the product temperature is close to the wet bulb temperature of the drying air. This period in the drying process is usually known as the constant rate drying period. The factors that determine the drying rate in this period are mainly external parameters such as air temperature and velocity and the surface area of the product. Fortes and Okos (1980) suggest that the drying rate during the constant rate period can be calculated by Equation (1).

$$\frac{dM}{dt} = \frac{h_{\mathrm{T}} A_{\mathrm{p}} (T_{\mathrm{a}} - T_{\mathrm{wb}})}{L}$$

where:

dM/dt = drying rate
h_{T} = convective heat transfer coefficient
A_{p} = surface area of product
T_{a} = dry bulb temperature of drying air
T_{wb} = wet bulb temperature of air at surface of the material

L = heat of vaporization of water

At a certain point - known as the critical moisture content - there is insufficient free moisture to maintain the maximum drying rate. The remaining moisture in the product is bound moisture and is held within its cell structure. This means that the moisture cannot move freely through the product to its surface. The rate of moisture movement to the surface of the product falls progressively and consequently the drying rate declines. This stage of the drying process is known as the falling rate period. Now the factors determining the drying rate are mainly internal parameters specific to the crop. These internal parameters are often conveniently grouped together and expressed as a diffusion coefficient or alternatively a drying constant. Mujumdar (1995) has described the latter as the most suitable parameter for the purposes of design and optimization. A commonly used form of algorithm for calculating the drying rate during the falling rate period is illustrated by Equation (2).

$$\frac{M - M_e}{M_0 - M_e} = e^{-kt}$$

where:

M = moisture content
M_e = equilibrium moisture content
M_0 = initial moisture content
k = drying constant
t = time

The ratio on the left-hand side of the equation is sometimes known as the moisture content ratio. For many crops, equations to determine the equilibrium moisture content (M_e) and the drying constant (k) can be found in the research literature, e.g., Hall (1957). Otherwise they must be determined experimentally.

The moisture content of a product can be expressed in two different ways - either as a percentage wet basis (% wb) or as percentage dry basis (% db). In the former case, the moisture content is the ratio of the amount of water in the product at any given time compared to the total weight at that time and is calculated using Equation (3).

$$M = \frac{100W_m}{W_m + W_{dm}}$$

where:

W_m = mass of moisture
W_{dm} = mass of bone dry material

The moisture content of a product expressed as a percentage dry basis is the ratio of the amount of water in the product at any time compared to the amount of dry matter in the product and is calculated using Equation (4).

$$M = \frac{100W_{\mathrm{m}}}{W_{\mathrm{dm}}}$$

The wet basis moisture content is mostly used by commercial producers while researchers and academic professionals use the dry basis moisture content. A comparison of various values of moisture content expressed as a wet and dry basis is given in Table 1.

Moisture Content - Dry Basis (%)	Moisture Content - Wet Basis (%)
400	80
300	75
200	67
100	50
50	33
25	20
15	13
10	9.1
5	4.8

Table 1 Comparison of moisture content values expressed on wet and dry bases

Large differences in the magnitude of the values of moisture content occur when the product is fresh but this declines as the product dries. It is important that the moisture content basis that is used when results are reported is defined.

Whichever basis is used, there are two moisture content levels which are of interest. These are the initial moisture content, i.e., when the crop is freshly harvested, and the moisture content which must be achieved by the drying system to ensure long-term safe storage - sometimes known as the safe moisture content. These two moisture content levels vary between crops and locations. Some typical values of each are given in Table 2.

Crop	Initial Moisture Content (%wb)	Safe Moisture Content (%wb)
Grapes	80	15-20
Carrots	70	5
Chilies	80	5
Bananas	80	15
Potatoes	75	13
Apricots	85	18

Table 2: Initial and safe moisture contents for some typical crops
(*source: Bansal and Misra, 1988*).

The quality of the final product is of great importance particularly to commercial producers because the sale of their product and the price received will depend greatly on the grade or quality produced. Final quality is judged variously depending on the crop but is likely to include final moisture content, color, taste and shape.

3. Sun vs. Solar Drying

The sun has been used for drying as long as humans have inhabited the planet and laying a product out in the sun to remove its moisture is known as sun drying. When sun drying, the temperature of the surrounding air remains at ambient temperature while the temperature of the product is raised by the direct absorption of solar radiation. Although sun drying is still by far the most common method of drying, it does have several inherent disadvantages. The unprotected crop can be damaged by rain, contaminated by dirt and animals and/or eaten by birds and insects. Since the temperatures attained during sun drying are usually lower than in a solar dryer, drying times are longer. This usually results in poorer final quality because of crop discoloration caused by enzymic and non-enzymic browning, and often because of the formation of moulds.

In a solar dryer however the temperature of the air surrounding the product is raised above the ambient air temperature. Depending on the type of solar dryer, the temperature of the product may also be raised by direct absorption of solar radiation. The temperatures in a solar dryer are higher than in sun drying and this reduces the drying time and usually improves the final product quality. Crop losses and spoilage from rain and animals are prevented because the crop is protected within the solar dryer.

4. Types of Solar Dryer

There are many different types of solar dryer but they can all be conveniently classified into three distinct categories depending on the mode of heat transfer from the sun to the product. This has led to the following definitions.

4.1 Direct Mode

In a direct mode solar dryer the crop is directly exposed to solar radiation. For this to occur, the structure containing the crop must be covered with a transparent material. The solar radiation passes through the glazing and is absorbed by the crop and its immediate surroundings. Most of the solar radiation is converted into heat, thus raising the temperature of the crop and its surroundings (Figure 1).

Figure 1: Direct mode solar dryer

The direct absorption of solar radiation by the crop is the most effective way of converting solar radiation into useful heat for drying. The final dried quality of some crops is also enhanced by direct exposure to solar radiation. For example, premium grade apricots have a deep orange color and this is produced if all remaining chlorophyll (or greenish color) has been destroyed. Ultraviolet solar radiation will produce this effect.

Because the crop itself directly absorbs solar radiation, crop temperatures are difficult to control and this is the main disadvantage of this type of dryer. Drying rates and final crop quality are very dependent on crop temperature. However the simplicity and relatively low cost of this type of dryer makes it attractive for both small- and large-scale producers. Direct mode solar dryers can range in capacity from a few kilograms to several metric tons.

4.2. Indirect Mode

In an indirect mode solar dryer, the crop is not directly exposed to solar radiation. The incident solar radiation is absorbed by some other surface - usually a solar collector - where it is converted into heat. The air for drying flows over this absorber and is heated. The warmed air is then used to transfer the heat to the crop located within an opaque structure.

For some crops, particularly herbs and some spices, the final quality is reduced if the product is exposed directly to solar radiation. The spice cardamom is one such example. Exposed to direct sunlight, the pods are prone to split and the chlorophyll is destroyed. Premium prices however are paid for cardamom pods which are whole and have a greenish color. An indirect mode solar dryer is therefore more suitable for this crop.

High and controllable temperatures can be achieved in this type of dryer if a fan is used to move the air through the solar collector. The main disadvantages of an indirect mode solar dryer are the additional cost and complexity involved in construction. Like direct mode dryers, the capacity can range from a few kilograms to several metric tons.

4.3. Mixed Mode

In some instances, a solar dryer uses a combination of direct and indirect modes known as a mixed mode solar dryer. In this type of solar dryer the crop temperature is raised by both direct absorption of solar radiation and heat transferred from another solar absorber. While mixed mode solar dryers probably have superior performance to direct or indirect mode solar dryers, in practice the additional cost and complexity of these systems tend to make them uneconomical and less popular in practice than the other two modes of dryer.

4.4. Further Classifications

All of the three principal solar dryer types (direct, indirect and mixed) can be further sub-divided depending on the method used to move air through the dryer, i.e., natural convection and forced convection.

4.4.1. Natural Convection

In a natural convection solar dryer, the air moves through the system because of the difference in density between the ambient air and the air inside the dryer. The air inside the dryer is less dense than the ambient air because it has been heated and contains more moisture. The less dense air rises up through the dryer and creates a small negative pressure that in turn induces fresh ambient air into the system. Because pressure differences are small, the airflow rates are also small. Researchers have reported air velocities in the range of 0.1-0.5 m s^{-1} (Moyls, 1986; Ayensu and Asiedu-Bondzie, 1986). Since the air temperatures in the dryer are dependent on solar radiation, the airflow in a natural convection system is also variable.

Airflow rates may be increased marginally through the addition of a solar chimney on the outlet side of the dryer to increase the density difference (Bassey, et al., 1994). However the relatively low and variable airflow inherent in a natural convection solar dryer is its main limitation. As a consequence, the performance is usually inferior to a forced convection system. On the other hand, a natural convection solar dryer has lower capital and running costs because there is no electric fan needed. This type of dryer is also sometimes the only choice in locations that do not have access to electricity.

4.4.2. Forced Convection

In a forced convection system, a fan is used to move air through the dryer. Higher air velocities - up to 3 m s^{-1} - through the crop usually improve drying rates especially in the constant rate drying period. The airflow rate can also be controlled and varied depending on the stage of drying. In addition, the quantity of the crop in the dryer can be increased because the fan can overcome any additional resistance to airflow.

The disadvantages of a forced convection system are the increased capital and running costs and the requirement for electricity. In commercial solar drying systems however the advantages mentioned usually far outweigh the disadvantages, and an electric fan is used if possible.

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Biographical Sketch

Dr R.J. Fuller has worked in the field of solar energy since 1978, firstly with the Commonwealth Scientific and Industrial Research Organisation (C.S.I.R.O.) of Australia, then with the Victorian Department of Agriculture and finally with The University of Melbourne. He has specialized in low temperature thermal applications of solar energy, particularly in agriculture, horticulture, aquaculture and solar industrial process heating. Trained as a mechanical engineer, Dr Fuller has Masters and Doctoral Degrees from the University of Melbourne.

His work in solar energy has covered design, simulation, development and demonstration projects in Australia and overseas. He has worked as a consultant in a number of countries across Asia and the Pacific on projects funded by organizations such as the United Nations, AusAid, the Forum Secretariat of the South Pacific and GTZ. Dr Fuller has published over 80 papers, articles, book chapters and booklets on solar energy and related topics.

Currently, Dr Fuller is a Principal Fellow in the International Technology Centre of Department of Civil and Environmental Engineering at The University of Melbourne where he teaches and supervises post-graduate students, particularly from developing countries, who are conducting research into renewable energy systems, energy planning and energy efficiency. He also works as a private consultant, particularly in the field of the simulation of the thermal performance of commercial buildings and on overseas aid projects, and has an active interest in a small business manufacturing solar dryers.