Manufacturing and Evaluating of Indirect Solar Dryers: A Case Study for the Kurdistan Region of Iraq

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Abstract—**Indirect solar drying uses solar radiation to heat air and dry agricultural products in harvest time to store them for a longer time and reduce waste. The dryer consists of a solar air heater collector, a drying chamber, and an air ventilation system. In this study, an indirect solar dryer system is constructed and ventilated with an electrical fan. Experiments are conducted on the system using eggplant as an agricultural sample on 2 consequent days (29th and 30th October 2022), to evaluate the system data recorded during the drying process in terms of the temperature for points in the system, solar radiation, and the sample mass. The temperature measurements are ambient, collector, and dried chamber outlet temperatures. The results show that the most effective time for solar drying is between 9:00 and 16:00, and the drying system air temperature is raised to about 40°C when solar radiation reached more than 600 W/m^2 in the noon time. The weighted mass is used to evaluate the drying process, and maximum drying rate and drying efficiency are obtained on the 1st day of the drying before noon time.**

***Index Terms*—Drying efficiency, Eggplant, Experimentation, Indirect solar dryer, Solar energy.**

I. Introduction

Solar radiation in the form of solar thermal energy is a suitable energy source and can be used in many applications, drying is one of these applications, particularly for fruits, vegetables, and agricultural grains. Iraq is within areas with high solar radiation intensity and long daylight hours, which makes this approach more feasible (Mahmood and Al-hassany, 2014; Jassim and Hassan, 2018).

Drying is a technique employed to extract moisture from agricultural goods, extending their storage duration. The ancient method of sun drying outdoors has been utilized for preserving edibles and crops. Nevertheless, this approach presents several drawbacks, such as product spoilage caused by elements such as rain, wind, moisture, and dust. There is also the risk of losses from animals and birds, along with the potential deterioration of harvested crops due to decomposition, insect infestations, fungi, and more. In addition, this process demands substantial manual labor, a significant time investment, and ample space for spreading out the items to facilitate drying (Khan, Kasi and Kasi, 2018; Hii, et al., 2012).

Indirect solar drying is one of the important preservation techniques for fruits and vegetables, to sustain the balance between population growth and food supply, food losses during harvesting and marketing should be minimized. The quality and quantity of agricultural produce suffer due to poor processing methods and a shortage of storage facilities. Many developing countries suffer considerable losses on the agricultural front. It is mentioned that post-harvesting loss of fruits and vegetables in developing countries is about 30–40% of total production (Lingayat, et al., 2020).

Indirect solar drying offers better control over drying and the product obtained is of better quality than sun drying, the foods to be dried are not exposed directly to solar radiation, so they are protected from the harmful effects of UV rays. Drying is carried out indirectly by convection between the heated air and the products to be dried (Krabch, et al., 2022).

Researchers in various geographical areas harnessed accessible solar power for dehydrating items and diverse culinary uses. Their efforts were primarily directed toward drying farm produce during the local harvest season, with some investigations also aimed at enhancing the efficiency of the employed technology.

One application of solar drying is to reduce the weight of waste; in a study, a solar dryer was investigated by Irene Montero, et al. to decrease by-products during olive oil production, and the drying process included olive pomace, olive mill wastewater, and sludge residue. The work aimed to reduce their high moisture content as drying constitutes the main stage for a possible bio-fuel conversion. The work dealt with the analysis of drying for the three main wastes from olive oil using a prototype dryer. Results showed the promising application of the dryer (Montero, et al., 2015).

Experimental research on the solar drying of Ataulfo mango was conducted in a region of Mexico, and the dried sample dried to 8% of its initial moisture in the ambient condition of an average temperature of 25°C and solar radiation 500 W/m^2 (Díaz, et al., 2017).

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A Proposal system using solar thermal energy in Iran, as presented Zaredar et al. to dehumidify products in the agricultural and pharmaceutical industries. The researchers suggested that the electronic and control system is embedded in data creation and airflow when necessary. The solar dryer is a device that performs the drying of different products with the use of renewable energies, in other words, no need of supplying the system with electricity performs dehumidifying operations (Zaredar, Effatnejad, and Behnam, 2018).

Different shapes of absorber plates in the collector were investigated to dry maize for Baghdad weather by a mixed-mode forced convection solar dryer. The study was carried out using three solar collector models: a collector with a flat plate, a V-corrugated plate, and tubes. Moreover, the three models were compared with traditional open sun drying. The obtained result showed that the maximum thermal efficiency of the solar collector was 78.5% for 0.057 kg/s when the V-corrugated plate shape was used as the absorber. Furthermore, the moisture content is reduced from the initial moisture content to 13.2% wet basis after about 5 h of drying (Jassim and Hassan, 2018).

A study that includes a hybrid photovoltaic-thermal double-pass counter-flow system connected with the mixed-mode solar dryer system was studied by Jadallah, Alsaadi and Hussien, 2020. The verification of the effectiveness and robustness of the system was explored by drying 300 g of slices of banana. The moisture content dried from 78% to 28.12% after 8 h of the drying process and the obtained range of air temperature is from 43.2 to 60.2°C. It was noticed that the highest thermal efficiency was 52.98% at 1:00 PM when the mass flow rate was 0.031 kg/s (Jadallah, Alsaadi, and Hussien, 2020).

The suggestion of employing phase change material as a means of storing thermal energy was put forward within the thermal framework of an indirect solar dryer. This proposal aimed to extend operational hours through the night. The study delved into the effectiveness of three different models, and the findings indicated an enhancement in the duration of effective drying hours (Ramirez, Palacio, and Carmona, 2020).

Effect of constructed material for constructing experimental model investigated by Fernandes et al., two designs of indirect solar dryers using two different constructed materials (wood and styrofoam) for domestic application and the result showed the possibility of dying fruits and vegetables up to 10% of their initial weight at low cost (Fernandes, Fernandes, and Tavares, 2022).

Using energy and exergy thermodynamic analysis to study the effects of air-drying parameters of the rosemary drying process in a hybrid-solar dryer was performed by Karami, et al. The studied parameters were air temperature and air velocity for optimizing the system operation. The findings showed that the exergy loss rate was affected by temperature and air velocity because the overall heat transfer coefficient was different under these conditions (Fernandes, Fernandes, and Tavares, 2022).

A single dryer compartment indirect solar dryer with a south-oriented roof was used to dry pearl in the Faculty of Sciences of Rabat city. Thermal performance and economic cost were investigated in the study, and the experimental results showed that the relative humidity inside the dryer can decrease by up to 10%, and the average temperature inside the dryer reached 50°C, allowing the pear to dry just after 24° h and it was concluded that solar dryer is less expensive than conventional two-compartment solar dryers (Krabch, et al., 2022).

A mathematical model based on the experimental model was derived to study design parameters in an indirect solar dryer in case of no load and full load operation capacity. It is concluded the drying efficiency of the solar dryer improved in the case of forced convection with the help of a fan (Kumar, et al., 2022)

This research investigates the potential for utilizing solar energy to achieve a sustainable food drying method. The aim is to address the issue of excessive wastage of agricultural produce, particularly fresh foods and fruits, during the harvest season in the Kurdistan Region of Iraq. The goal is also to extend the shelf life of these food items.

II. Materials and Methods

A. Experimental Setup

An experimental greenhouse indirect forced convection solar dryer was designed and installed in location Koysinjaq-Erbil-Kurdistan Region of Iraq (36.07, N, 44.65 E), Iraq. The solar collector of the dryer is 80 cm in width, 135 cm in length, and 5 cm in height, and the drying chamber dimensions are 50 cm in length, 80 cm in width, and 60 cm in height. The photograph of the dryer is shown in Fig. 1.

The structure of the dryer is made from steel and to minimize heat loss, the system is covered with an ALUCOBOND sandwich. Components and specifications of the solar dryer are shown in Table I.

The drying chamber had three food shelf trays with the dimension of 80 cm × 50 cm and there was 18 cm distance between each tray. The shelves were made from (12 mm × 12 mm) meshed stainless steel to avoid rusting. This meshed hole of the shelf helps pass hot air through the food to be dried. The system is ventilated with a 16 W fan with a volumetric flow rate of 90 m^3/h.

Experiments to evaluate the drying performance of the indirect solar dryer prototypes were conducted under the Koysinjaq local weather conditions. The experiments were conducted from 29th to October 30th, 2022.

The measured parameters in the experimental work were temperatures of many points in the system as well as solar heat flux and mass of the drying foods.

The measured temperature points include the outside ambient air temperature, collector outlet temperature (cabinet inlet), and air temperature outlet of the cabinet (chamber).

The temperature measuring points are recorded by the temperature data logger V2 and a DS18B20 digital temperature sensor (3 wire) with accuracy: ±0.5°C over a full −50–125°C temperature range, compatible with Arduino Bluetooth module HC05 at 5 min-intervals temperature data logging.

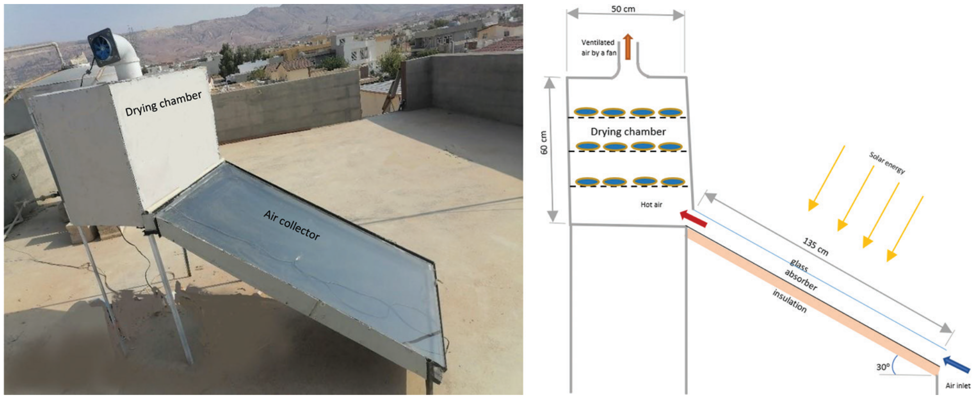

Fig. 1. Photograph and schematic diagram of the experimental model

Table 1
Specifications of the experimental model

Item	Description or dimensions
Location of the dryer	Koysenjaq-Erbil-Iraq (36.07, N, 44.65 E)
Standard time of the location	UTC +3
Drying food quantity	3 kg eggplants
Solar collector dimension	W=80 cm, L=135 cm, H=5 cm
Solar collector area	1 m^2
Solar collector transparent glass thickness	4 mm
Collector's absorber plate material and thickness	Steel, 0.6 mm
Absorber plate painting color	Black
Fan volumetric flow rate	90 m^3/h
Air exit cross-section diameter	10 cm
Drying chamber	W=80 cm, L=50 cm, H=60 cm
Number of shelf trays	3
Drying shelf trays dimensions	80 cm × 50 cm
Distance between trays	18 cm
Collector's tilt angle	30 due the South

Solar intensity is recorded every 5 min logging by precision; VOLTCRAFT DL-131 LUX Solar data logger instrument with a measuring range (0–2000 W/m^2) with accuracy:±10 W/m^2.

The mass of dried food samples was measured 3 times every day during drying with an accurate electronic weighing scale with accuracy ±0.5 g ranging from 0 to 5000 g.

B. Drying Performance of the System

To assess the system's effectiveness, eggplants were selected as a representative sample due to their capacity to absorb surplus production during the harvest season in the area, as well as their ability to extend shelf life and enhance the culinary experience.

An eggplant sample was washed with clean water after that slices were cut with a 12 mm thickness to be dried in the solar dryer. The samples were left to water to be dried before they were uniformly distributed between the chamber shelves, and the weight of the samples was scaled.

It is recommended that the drying process take place from 9:00 AM to 4:00 pm in short daytime, in that period solar thermal collector has maximum efficiency for drying grains (Khalil et al., 2012).

The essential measuring parameters taken in this study were ambient air temperature, collector outlet temperature, leaving the drying chamber air temperature, solar heat radiation, and weight of dried food. The measured parameters were used to evaluate the performance of the indirect solar drying system.

During the drying process, the moisture content in the food decreased and a percentage of wet moisture content can be estimated by the following equations (Ssemwanga, Makule, and Kayondo, 2020):

$$Mc = [(m_i - m_d) / m_i] * 100\% \tag{1}$$

Where:

m_i is the mass of the sample before drying

m_d is the mass of the sample after drying.

The evaporated water mass is determined by the following equation (Cherotich and Simate, 2016):

$$m_w = [m_i(m_I - m_F) / (100 - m_F)] * 100 \tag{2}$$

Where:

M_I is the initial moisture content and M_F is the final moisture content.

The drying rate of the food was determined by the equation (Brenndorfer, et al., 1987):

$$m_{dr} = m_w / t_d \tag{3}$$

where td is the considerable drying time.

The drying system efficiency of a solar dryer is the ratio of the energy needed to evaporate moisture from the dried sample to the solar heat energy to the dryer and can be calculated by (Wankhade, Sapkal, and Sapka, 2014):

$$\eta_s = (m_w h_{fg}) / (I_s A_c t_d) \tag{4}$$

Where:

I_s it solar insolation on the collector in W/m^2.

h_{fg} is the latent heat vaporization for water taken from steam tables = 2270 kJ/kg at a mean temperature $[(T_{coll}+T_o)/2]$ in J/kg, and T_{coll} and T_o are the collector and chamber outlet temperatures at °C (Chouicha, et al., 2013).

III. Results and Discussion

Solar radiation and ambient temperature are factors affecting the performance of the drying process. Fig. 2 shows the variation of solar intensity and temperature profiles of ambient, collector exit, and chamber outlet of the dryers with the time of the day during solar drying on October 29, 2022. The findings showed that with increasing solar radiation intensity, the collector and dry chamber temperature rises and the maximum temperature was recorded at noon time when the solar radiation reaches its peak. The maximum solar radiation intensity, collector temperature, and drying chamber temperature were 663 W/m^2, 43.3°C, and 38.1°C, respectively; on the other hand, the ambient temperature reaches its maximum value 1 h after noon time after that the temperature falls due to diminishing solar radiation.

Fig. 3 shows the variation of temperature profiles and solar insolation on October 30, 2022, it can be noticed that the trend of the curve is similar to the previous day but the collector temperature reached a higher value (more than 45°C), and ambient temperature was higher compared to the previous day (the recorded ambient temperatures were 27.8°C and 28.3°C for the consequent days, respectively).

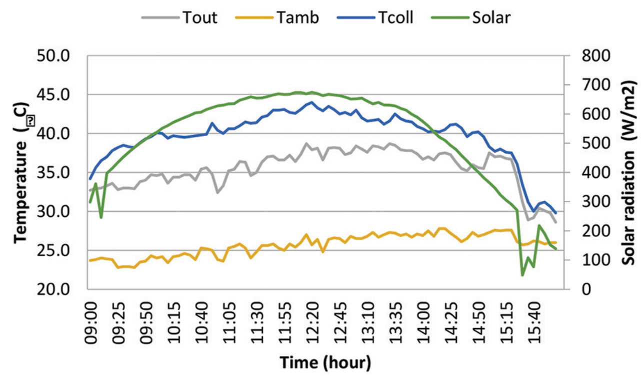

Fig. 2. Ambient, collector, dry chamber air leaving temperatures, and solar radiation on October 29th, 2022.

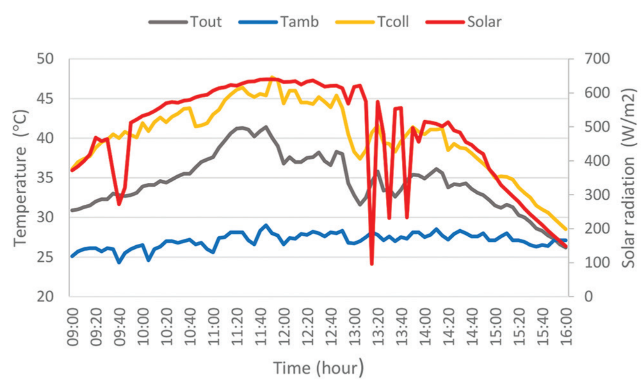

Fig. 3. Ambient, collector, dry chamber air leaving temperatures, and solar radiation on October 30th, 2022.

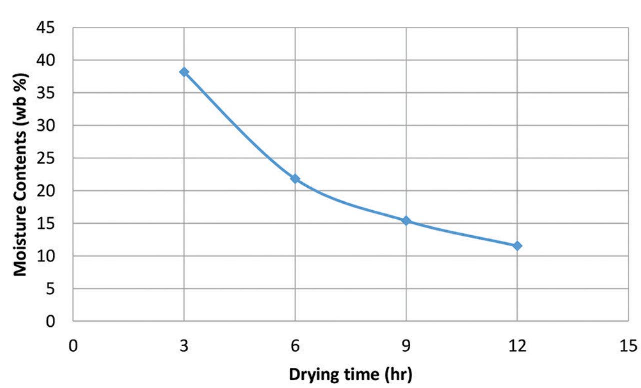

Fig. 4. Relation between the moisture content of the sample and drying time for the system.

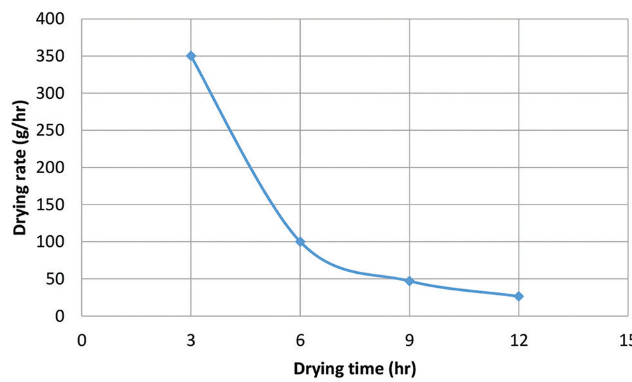

Fig. 5. The variation of drying rate with time for the two consequent drying days.

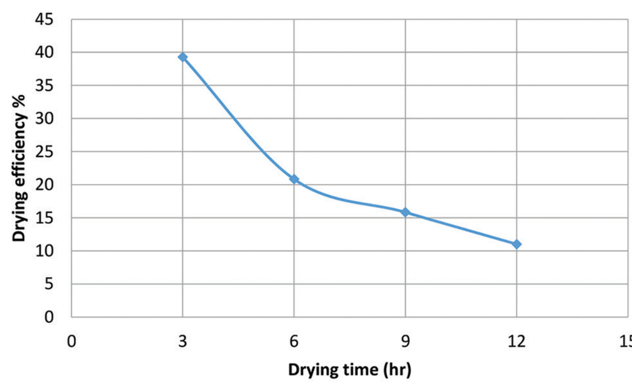

Fig. 6. Drying efficiency during active drying process time

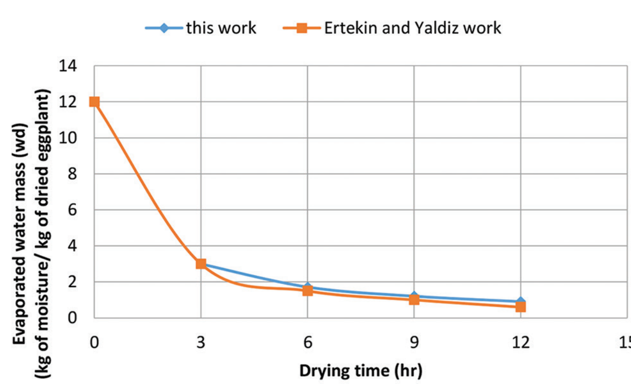

Fig. 7. Comparison between this work to other work at an average drying temperature of 40°C.

Fig. 8. Dried eggplant (a) fresh eggplant before drying (b) 1st day after drying (c) 2nd day after drying.

For both experimental days, it can be noticed that in the early morning daytime before 9:00 and in the late afternoon daytime after 15:00 h, the temperature difference between ambient and collector decreased resulting non-effecting period for solar drying in that season.

Fig. 4 shows the variation of moisture content with the time of active drying hour of 2 days (October 29th, 2022 and October 30th, 2022) by the indirect solar drying, the trend of the curve shows moisture content reduction with the time of drying, the most effective moisture reduction is observed in the early time of the drying process, during first 3 h of drying the eggplant lost 60% of its moisture based on wet analysis after 12 h of solar drying only about 10% of the moisture remains in the sample.

The drying duration is the main factor to take into account when assessing a solar dryer system. It is measured in terms of time such as hours or days from the moment the fresh product is placed into the dryer until it reaches the desired moisture level. Drying with higher drying temperatures speed up the drying process, but also it raises the risk of damaging the product in terms of loss of color, flavor, aroma, and vitamins (Leon, Kumar, and Bhattacharya, 2002).

The drying rate is an indication of how fast dehydration takes place in the dryer. Fig. 5 shows the change in the drying rate of the sample with time in the 2 days of drying, it is noticed that there is a sharp fall of the curve trend in early times of drying referring in significant evaporation process in the sample due to rise temperature and forced convection by ventilating the drying chamber with the fan. The rate of the drying process decreases with time, in the late time of drying, the rate tends approach to be constant.

The drying efficiency term is used to measure the overall effectiveness of a drying system, an average drying efficiency for every 3 h is illustrated in Fig. 6, the figure shows that maximum drying efficiency is obtained in the early times of drying, the 1st h of drying shows about 40% and decreased with time due to fall in the evaporation rate in the sample, the minimum value of efficiency is obtained in the last hour in the 2nd day of the solar drying to reach 11%.

The validation of the authenticity of this study is established through a comparison with prior research concerning the dehydration of eggplants. This current research is contrasted with the findings of (Ertekin and Yaldiz, 2004) and visually presented in Fig. 7. The drying patterns of eggplants, specifically the reduction of moisture content during the drying procedure, exhibit a parallel behavior between the two datasets. However, a minor distinction between the two curves emerges at an average drying temperature of 40°C.

The utilization of the indirect solar dryer system resulted in achieving high-quality dried eggplants, as determined by their visual attributes, consistency, and fragrance. The images presented in Fig. 8 depict the eggplant samples before drying and after each day of the drying process, illustrating the consistent and desirable coloration observed in the dried samples.

IV. Conclusion

An indirect type forced convection solar dryer has been designed and fabricated for drying agriculture products; in this study, eggplant was selected to be dried, and the samples were dried for 2 days, it is concluded that:

- The system is suitable for drying foods in the region even in the late summer and fall seasons when the weather is dry and abundant solar radiation is available and it will have a good impact on the economy in the region
- The highest temperature rise in the system is obtained by the collector afternoon time
- During the period of early morning and late afternoon when the solar insolation diminishes, the drying effect of the difference between the collector and ambient temperatures is reduced, de-activate the drying effect in these periods.
- The highest evaporation rate and system efficiency are in the initial time of the drying process on the 1st day.

References

Brenndorfer, B., Kennedy, L., Bateman, C., Trim, D. S., Mrema, G. C., and Wereko-Brobby, C., 1987. Solar Dryers-their Role in Post-harvest Processing. 1st ed. Commonwealth Science Council, London.

Cherotich, S., and Simate, I. N., 2016. Experimental investigation and mathematical modelling of a natural convection solar tunnel dryer. *International Journal of Scientific and Engineering Research*, 7(5), pp.597-603.

Chouicha, S., Boubekri, A., Mennouche, D., and Berrbeuh, M. H., 2013. Solar drying of sliced potatoes. an experimental investigation. *Energy Procedia*, 36, pp.1276-1285.

Díaz, R.I., Gómez, R.A.J., Danguillecourt, O.L., de Paz, P.L., Vázquez, N.F., and Duharte, G.R.I., 2017. Design, construction and evaluation of a solar dryer for Ataulfo mango. *Revista Mexicana de Ciencias Agrícolas*, 8, pp.1719-1732.

Ertekin, C., and Yaldiz, O., 2004. Drying of eggplant and selection of a suitable thin layer drying model. *Journal of Food Engineering*, 63(3), pp.349-359.

Fernandes, L., Fernandes, J.R., and Tavares, P.B., 2022. Design of a friendly solar food dryer for domestic over-production. *Solar*, 2(4), pp.495-508.

Hii, C.L., Jangam, S.V., Ong, S.P., and Mujumdar, A.S., 2012. *Solar Drying: Fundamentals, Applications and Innovations*. TPR Group Publication, Singapore. Available from: https://www.dergipark.gov.tr/sjmakeu [Last accessesd on 2022 Oct].

Jadallah, A., Alsaadi, M., and Hussien, S., 2020. The hybrid (PVT) double-pass system with a mixed-mode solar dryer for drying banana. *Engineering and Technology Journal*, 38(8), pp.1214-1225.

Jassim, N.A., and Hassan, S.S., 2018. *Thermal Performance Evaluation of Solar Air Dryer for Food Drying in Iraq*. Available from: https://www.researchgate.net/publication/324991813 [Last accessed on 2022 Nov].

Khan, Y., Kasi, J.K., and Kasi, A.K., 2018. Dehydration of vegetables by using indirect solar dryer. *Techno-Science Scientific Journal of Mehmet Akif Ersoy University*, 1(1), pp.22-28.

Karami, H., Kaveh, M., Golpour, I., Khalife, E., Rusinek, R., Dobrzański, B. Jr., and Gancarz, M., 2021. Thermodynamic evaluation of the forced convective hybrid-solar dryer during drying process of rosemary (Rosmarinus officinalis l.) leaves. *Energies*, 14(18), p.5835.

Khalil, M. H., Ramzan, M., Rahman, M. U., and Khan, M. A., 2012. Development and evaluation of a solar thermal collector designed for drying grain. *Iranica Journal of Energy and Environment*, 3(4), pp.380-384.

Krabch, H., Tadili, R., Idrissi, A., and Bargach, M., 2022. Indirect solar dryer with a single compartment for food drying. Application to the drying of the pear. *Solar Energy*, 240, pp.131-139.

Kumar, A., Singh, K. U., Singh, M. K., Kushwaha, A. K. S., and Kumar, A., 2022. Design and fabrication of solar dryer system for food preservation of vegetables or fruit. *Journal of Food Quality*, 2022, p.6564933.

Leon, M.A., Kumar, S., and Bhattacharya, S.C., 2002. A comprehensive procedure for performance evaluation of solar food dryers. *Renewable and Sustainable Energy Reviews*, 6(4), pp.367-393.

Lingayat, A.B., Chandramohan, V.P., Raju, V.R.K., and Meda, V., 2020. A review on indirect type solar dryers for agricultural crops-dryer setup, its performance, energy storage and important highlights. *Applied Energy*, 258, p.114005.

Mahmood, F.H., and Al-Hassany, G.S., 2014. Study global solar radiation based on sunshine hours in Iraq. *Iraqi Journal of Science*, 55(4), pp.1663-1674.

Montero, I., Miranda, M.T., Sepúlveda F.J., Arranz, J.I., Rojas, C.V., and Nogales, S., 2015. Solar dryer application for olive oil mill wastes. *Energies*, 8(12), pp.14049-14063.

Ramirez, C., Palacio, M., and Carmona, M., 2020. Reduced model and comparative analysis of the thermal performance of indirect solar dryer with and without PCM. *Energies*, 13(20), p.5508.

Ssemwanga, M., Makule, E., and Kayondo, S.I., 2020. Performance analysis of an improved solar dryer integrated with multiple metallic solar concentrators for drying fruits. *Solar Energy*, 204, pp.419-428.

Wankhade, P. K., Sapkal, R. S., and Sapka, V. S., 2014. Design and performance evaluation of a solar dryer. *Journal of Mechanical and Civil Engineering*, 11, pp. 70-73.

Zaredar, A., Effatnejad, R., and Behnam, B., 2018. Construction of an indirect solar dryer with a photovoltaic system and optimised speed control. *IET Renewable Power Generation*, 12(15), pp.1807-1812.