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RESEARCH ARTICLE

DETERMINATION OF A CERTAIN NUMBER OF DRYING PARAMETERS OF A SOLAR DRYER EQUIPPED WITH A CONCRETE STORAGE SYSTEM

Germain Wende Pouiré OUEDRAOGO[1,3]*,Edmond BONKOUNGOU[3], Boureima KABORE[2,3]
Alain M. E. Kombasseré[3], Salifou OUEDRAOGO[3]and Sié KAM[3]

[1]Ecole Supérieure d'Ingénierie (ESI), Université de Fada N'Gourma, Fada N'Gourma, Burkina Faso;
[2]Unité de Formation et de Recherche Sciences et Technologies (UR-ST), Université Norbert ZONGO, Koudougou, Burkina Faso;
[3]Laboratoire d'Energies Thermiques Renouvelables, Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.

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ABSTRACT

The conservation of agricultural products constitutes a problem for Burkinabè farmers in particular. They use more preservation methods including solar drying. However, the majority place their products on plastic films, mats, even on the ground under solar radiation and exposed to insects, animals, wind or dust. In order to improve drying and hygiene conditions, several solar dryers have been invented but do not have a storage system that can continue drying after sunset. It is in this sense of solving this problem that we set out to design a solar dryer with energy storage.The experimental tests made it possible to observe a difference of 8°C and 13°C at 6 p.m. between the temperature of the concrete (our storage system) and respectively the ambient temperature and that at the outlet of the solar collector. In addition, the overall efficiency of the solar collector is between 5% and 20% depending on the irradiation. The quantity of water lost by the okra in each rack during drying is between 1347g and 1352g for an initial mass of 1500g.

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INTRODUCTION

Drying is one of the main methods of preserving perishable products used by humans (Y. Mohana *et al*, 2020; Anand Chavan *et al* 2020).It helps extend shelf life, reduce packaging costs, improve transport capacity and give a better appearance to products while preserving their taste and nutritional content (Mahmoud S. *et al*., 2023). The process consists of eliminating water in food, which will stop the proliferation of bacteria, yeasts and molds, which cause food spoilage (Halil A., 2020). Solar drying is widely practiced in the preservation of agricultural products and constitutes a complex process involving simultaneous transfers of mass and heat (MC. Ndukwu*et al*,2023;Ouedraogo G *et al*, 2022; Lingayat*et al*., 2020).There are several models of solar dryers depending on the technology used and the way in which solar radiation is converted (Ouedraogo G et al., 2021).The use of solar dryers saves 27 % to 80% of electrical energy and can be done in rural areas without access to the electricity grid (Udomkun P. et al, 2020).The solar dryer which is the subject of this study is an indirect solar dryer operating in natural convection and having an energy storage system. It was designed following a simulation on COMSOL MULTIPHYSIC allowing its thermal behavior to be evaluated during the flow of air in natural convection within it (Kam S. et al, 2017). The estimated air temperature inside the drying chamber is between 28°C and 60°C during the day.

Our objective is to carry out experimental tests on a device designed to observe the thermal behavior of the air in the vacuum dryer and carry out the convective drying process of okra. This will allow us to have an idea of the temperature variation, the performance of the solar collector, the physico-chemical properties of the dried okra.

Description of the Solar Dryer:The dryer in Figure 1 is made up of two essential parts, namely the solar collector and the desiccation chamber.The solar collector is the part where the conversion of solar radiation into heat necessary to extract moisture from a product takes place. It has a volume of $\mathbf{1,047m^3}$and is made up of:

A concrete slab 10cm thick and in the shape of a decagon with a surface area of 6.28 m^2. Concrete is the material used for storing heat during the day. This heat will be released as soon as the temperature of the surrounding environment drops compared to the temperature of the material.

10 panes of glass thick $0,5cm$and inclined at an angle of 45° to the horizontal. The total surface area of the windows is estimated at 3.7056 m^2or 0.37056 m^2per window.

The desiccation chamber or drying chamber is the part where the products to be dried are stored. It is made from 1.5mm thick metal sheets and covered with 5mm thick plywood sheets to act as thermal insulation. It has the shape of a hut whose volume is estimated at $2,355m^3$a height of 1.20m. It contains three (03) racks each having a surface d$e1,57m^2$.

Corresponding author: Germain Wende Pouiré OUEDRAOGO,
Ecole Supérieure d'Ingénierie (ESI), Université de Fada N'Gourma, Fada N'Gourma, Burkina Faso

A chimney allows air to escape after passing through the drying chamber. It is covered by a cone of volume 0.2125 m^3.Figure 1 shows the photo of the dryer.

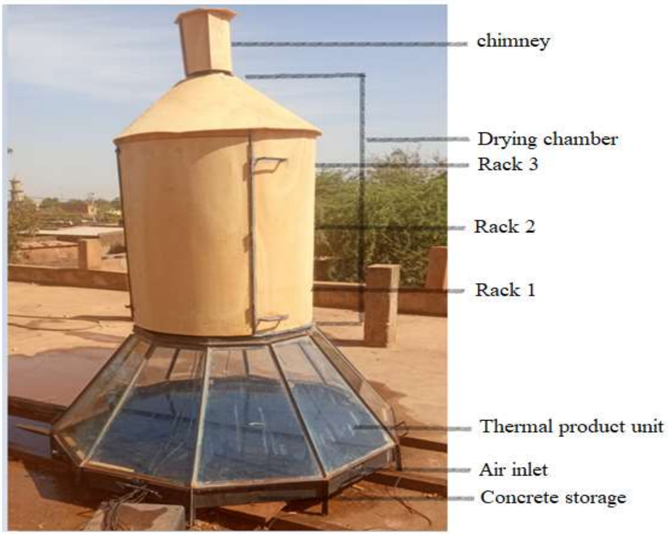

Figure 1. Photo of the dryer

Experimental protocol: The tests were carried out in two stages. The first concerned the tests on the vacuum dryer on November 13, 2020 where we measured the temperatures and solar irradiation. Type K thermocouples were placed on the dryer in several locations to record temperature values. A pyranometer was placed next to the dryer to measure solar irradiation. The recording of the values was possible thanks to the Midi LOGGER GL220.

The second concerned the convective drying process of okra:The okra was washed to remove impurities and then spread to allow surface water to evaporate. Then we cut it into a thin layer 1cm thick and placed it on the racks. The initial mass of okra to be dried per rack is 1.5 kg, or 4.5 kg of okra in total in the dryer.The drying process lasted three days (April 25, 26 and 27, 2021) during which the mass of the okra from the three racks was weighed every hour from 8 a.m. to 5 p.m. using an electronic scale. After the last weighing of the day, the product remains inside the dryer overnight where drying continues thanks to the energy stored by the concrete absorber. Drying stops after obtaining the same mass during three (03) successive weighings at each rack.

RESULTS AND DISCUSSIONS

Thermal performance of the vacuum dryer: The thermal parameters to be evaluated are the variation in air temperature inside the dryer, the quantity of energy stored and the efficiency of the vacuum dryer.

Solar irradiation: Figure 2 shows the evolution of solar irradiation during the day of November 13, 2020.

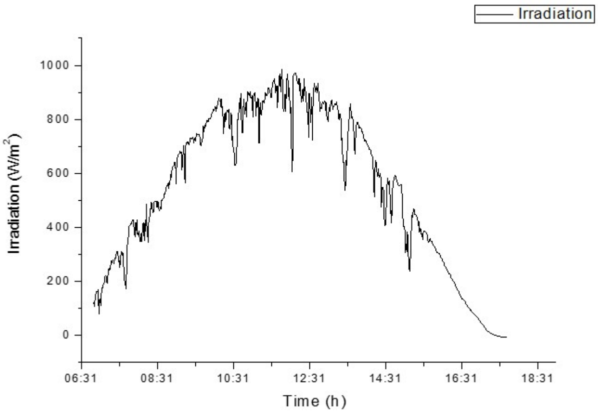

Figure 2. Solar irradiation on 11/13/2020

We observe between 7 a.m. and 12:20 p.m. an increasing fluctuation in solar irradiation which goes from 150 W/m² to 1000W/m². From 12:20 p.m. to 6 p.m. at sunset, we observe a decreasing fluctuation in irradiation going from 1000W/m² to 20W/m². The sudden drops observed in the solar radiation graph are caused by certain cloudy passages.

Air temperatures in the dryer: Figure 3 shows the variations in air temperatures at the inlet and outlet of the dryer chamber, the ambient temperature and that of the concrete. Figure 4 shows the variations in drying air temperatures at the level of the three racks.

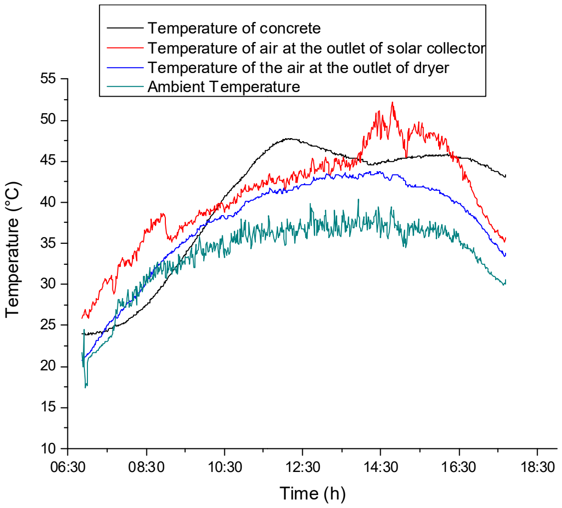

Figure 3. Variation of temperature in the dryer

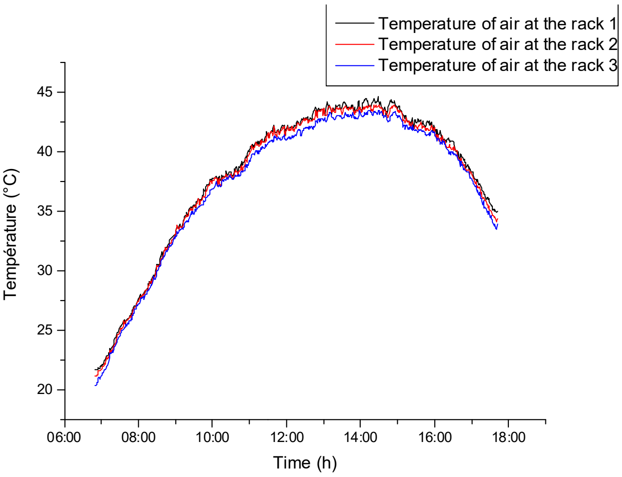

Figure 4. Variation of air temperature on racks 1, 2 and 3

The different temperatures measured depend on the variation in solar irradiation during the day. Ambient temperature is the lowest temperature compared to other temperatures in the dryer. The ambient air enters the dryer at a low temperature and is heated using the collector to give higher temperatures. It varies from 21.7°C at 7 a.m. to reach 40.4°C at 1:55 p.m. then decreases until reaching a temperature of 30.5°C at 6 p.m. The air temperature at the outlet of the solar collector or at the entrance to the drying chamber is higher than the other temperatures between 7 a.m. and 10:10 a.m. then between 2 p.m. and 4:20 p.m. It varies from 25.8°C at 7 a.m. and reaches a maximum of 52.2°C at 2:48 p.m. then decreases to 35.7°C at 6 p.m. The air temperature at the outlet of the dryer is lower than that at the entrance to the drying chamber. It varies from 20.7°C to 43.8°C at 2:31 p.m. then from 43.8°C to 33.8°C at 6 p.m.We observe between 10:10 a.m. and 2 p.m. that the concrete temperature is higher than the others with a maximum value of 47.6°C at 12:07 p.m. then after 4:20 p.m. where solar radiation becomes weak. At 6 p.m., the concrete temperature is 43.4°C, a difference of 8.4°C with the air temperature at the outlet of the solar collector and 13°C with the ambient air temperature. This shows that the drying process can continue and the concrete will be the new heat source. We observe in Figure 4 that the temperature of the drying air at the level of the first rack is slightly higher than that of the second rack as well as that of the third rack. The maximum values are 44.7°C at 2:48 p.m., 44°C at 2:30 p.m. and 43.3°C at 2:26 p.m. respectively for rack 1, rack 2 and rack 3. We also see that the maximum is reached at almost the same time. These temperatures varying from 22°C to 44.7°C are indicated for drying agri-food products (Daguenet Michel, Unesco 1985; Vishnuvardhan Reddy Mugi et al 2021).

Performance of the solar collector: The efficiency is defined as the ratio between the useful heat and the solar radiation incident on the collector plane. The efficiency of our device was calculated using equation 1.

$$\eta = \frac{C_P.m_a.(T_{as}-T_{amb})}{A_S.I}(1)$$

Where C_P is the specific heat of air ($J/kg°C^{-1}$), T_{as} and $T_{amb}$the absorber and ambient temperatures (°C), A_S the total surface of the collector (m^2), I the solar radiation (W/m^2) and m_a the mass flow rate of the air (kg/m^3).

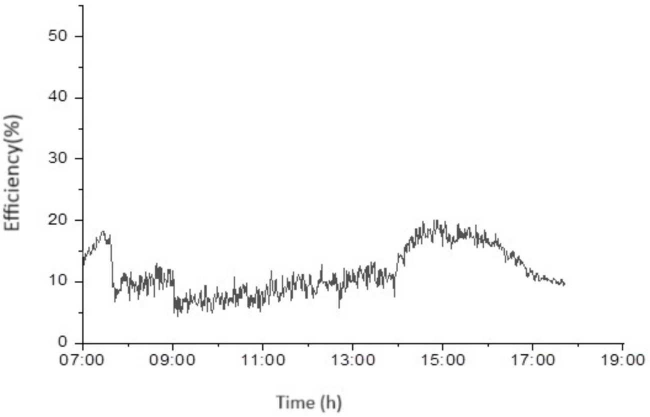

Figure 5. Evolution of sensor performance during the day of November 13, 2020

The efficiency of the solar collector depends on the solar radiation and the air flow in the collector. During the day of 11/13/2020, the solar collector efficiency values are between 5% and 20%. Figure 5 also shows that the sensor efficiency increases at the end of the day (between 2 p.m. and 4 p.m.) despite the drop in solar radiation. This phenomenon is the result of the energy stored by the concrete at the time of strong solar irradiation.

Drying kinetics: Drying the okra allowed us to represent the variation in water content, drying speed.

Variation in the water content of okra at the three (03) racks as a function of time: Figure 6 shows the evolution of the water content of okra during drying. Equation 2 was used for calculation of dry-based moisture content of okra χ.

$$\chi = \frac{m(t)-m_s}{m_s}(2)$$

The first part of the curve presents the evolution of the water content during the day of April 25, 2021. The initial water content of the okra at the level of racks 1, 2, 3 are respectively 9.638 kg of water/kg of dry matter, 9.714 kg of water/kg of dry matter and 9.791 kg of water/kg of dry matter. After 9 hours of sunny drying, the water content increases to 3.971 kg of water/kg of dry matter for rack no. 1, 4.907 kg of water/kg of dry matter for rack 2 and 4.582 kg of water/kg of dry matter. This made it possible to eliminate 799g of water, 611g of water and 724g of water contained in the okra spread respectively on each rack.

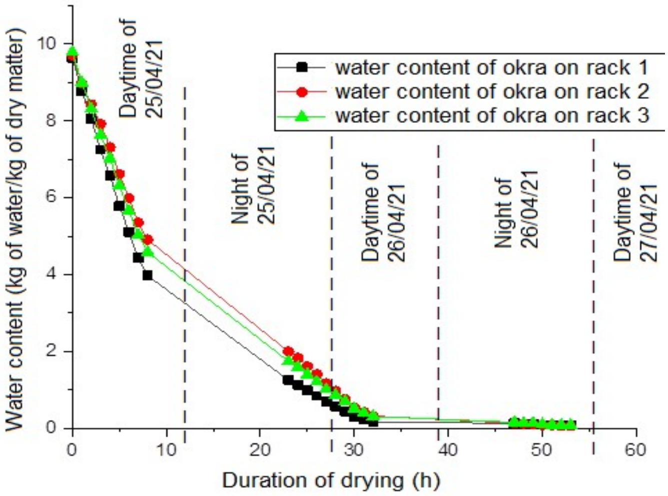

Figure 6: Variation in the water content of okra from the three racks

The second part illustrates the trend in the evolution of the water content during the night of April 25 to 26, 2021. From 5 p.m. to 8 a.m., drying continued thanks to the heat stored in the concrete absorber and the heat stored by the product. This made it possible to achieve respectively 1.248 kg of water/kg of dry matter, 1.992 kg of water/kg of dry matter and 1.741 kg of water/kg of dry matter at the level of rack 1, 2 and 3, April 26 at 8 a.m. During this period, the quantity of water lost is estimated at 384g, 408g and 395g per rack.The third part represents the second day of drying (April 26, 2021). At the end of this day, the water contents were 0.163 kg of water/kg of dry matter, 0.314 kg of water/kg of dry matter and 0.302 kg of water/kg of dry matter respectively for the racks 1, 2 and 3, i.e. a reduction in the quantity of water of 153g, 235g and 200g. During this sunny day, the amount extracted is about half the amount of water extracted during the previous night. This is explained by the fact that the product tends towards its dry state.The fourth part of the curve presents the trends of the second night of drying (April 26 to 27). We see that the curve always decreases and the three curves converge towards the same value. The quantity of water lost is respectively 6g, 26g and 21g per rack. It is low compared to previous amounts of water loss. On April 27, at 8 a.m. the water content of the racks was 0.120 kg of water/kg of dry matter for rack 1, 0.128 kg of water/kg of dry matter for rack 2 and 0.151 kg of water/kg of dry matter for rack 3.The fifth part shows us the variation in the water content of okra for the day of April 27. The curves are almost confused as we tend towards the end of drying. That day, we stopped drying at 2 p.m. but the mass of the product on rack no. 1 stopped varying from 11 a.m. and those on racks 2 and 3 from 1 p.m. The quantity of water extracted is 5g, 10g and 10g per rack. Thus, the final water content for racks 1,2 and 3 are respectively 0.085 kg of water/kg of dry matter, 0.057 kg of water/kg of dry matter and 0.079 kg of water/kg of dry matter.The okra from rack 1 required a duration of 21 sunny hours and 30 hours not sunny to eliminate 1347g of water while the okra from racks 2 and 3 lost respectively 1290g and 1350g of water for one duration of 23 hours sunny and 30 hours not sunny. Rack 1 being located at the entrance to the drying chamber, the rising hot air comes into contact with the products on this rack before reaching the other two located higher up. Which explains why it dries faster than the others. This observation was made by Ouedraogo et al. in 2017 with the solar tower dryer and also by Pakouzou et al. in 2021.

Table1 shows the evolution of the water content and mass of the okra per rack at the beginning and at the end of the drying operation.

Drying speed of the okra spread on the three racks: Due to the great diversity of products to be dried, determining the drying speed using experimental measurements remains one of the best means of characterizing the behavior of products during drying.

Table 1. Water content and mass of okra at the start and end of drying

Product	Start of drying		End of drying	
	Mass (g)	Water content (kg of water.kg $^{-1}$ of material)	Mass (g)	Water content (kg of water.kg $^{-1}$ of material)
Okra from rack 1	1500	9,638	153	0.085
Okra from rack 2	1500	9,714	148	0.057
Okra from rack 3	1500	9,791	150	0.079

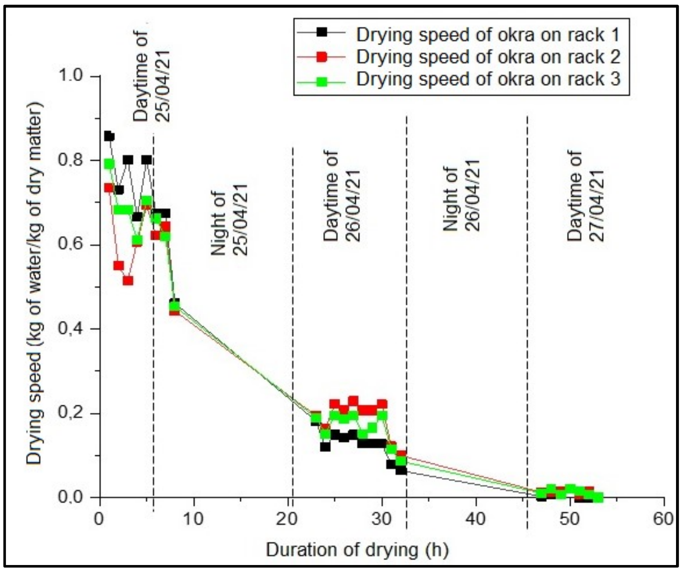

Figure 7. Variation in the drying speed of okra from the three racks as a function of time

Table 2. Drying speed at the start and end of drying

Product	Drying speed at the start of drying (kg of water.kg $^{-1}$ of material.h $^{-1}$)	Drying speed at the end of drying (kg of water.kg $^{-1}$ of material.h $^{-1}$)
Okra from rack 1	0.858	0.021
Okra from rack 2	0.735	0.014
Okra from rack 3	0.719	0.007

Table 3. Makes a comparison with the literature

Authors	$D_{eff}(10^{-10}m^2s^{-1})$	Radius in cm
Present work	17.84 – 18.52	1
Ouedraogo et al.	47.8	1
Pakouzou et al.	16.49 – 22.72	0.7
Dincer et al.	5.67	Unspecified

Figure 7 shows us the drying speeds of okra from the three racks during drying. The speeds are obtained from equation (3) where $\chi$is the water content and $t_2 - t_1$the time step.

$$-\frac{d\chi}{dt} = \frac{\chi(t_2)-\chi(t_1)}{t_2-t_1}(3)$$

The curve has four distinct parts: The first part of the curve shows a fluctuation in the drying speed during the sunny day. This fluctuation is due to the variation in solar radiation, the heating of the products and the different openings of the drying chamber for weighing. Drying rates fluctuated between 0.858 kg water/kg dry matter/h and 0.46 kg water/kg dry matter/h, between 0.735 kg water/kg dry matter/h and 0.44 kg of water/kg of dry matter/h then between 0.791 kg of water/kg of dry matter/h and 0.45 kg of water/kg of dry matter/h respectively for racks 1, 2 and 3.During the night, the drying speed decreased until it reached 0.181 kg of water/kg of dry matter/h for rack no. 1, 0.194 kg of water/kg of dry matter/h for rack 2 and 0.189 kg of water/kg of dry matter/h for rack 3. This linear decrease is due to the fact that the water in the product slowly decreases near its dry state and also thanks to the cooling of the concrete. The heating phase is not visible on our curve, this is due to the fairly long duration (1 hour) which separates two successive migration of water from the interior of the okra towards its surface because the free water has already evaporated.Table 2 shows us the evolution of the drying speed from the start and end of the drying operation.

Diffusion coefficient of okra: The diffusion coefficient is a physical quantity depending on the shape of the product. This diffusion coefficient makes it possible to evaluate the speed of movement of water vapor along the product. To determine this coefficient, we applied Fick's second law (equation 4) and its analytical form (equation 5) to the experimental results obtained during the solar drying of okra.

$$\frac{\partial\chi}{\partial t} = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(D_{eff} r\frac{\partial\chi}{\partial r}\right)\right) + \frac{\partial}{\partial z}\left(D_{eff} r\frac{\partial\chi}{\partial z}\right) \quad (4)$$

$$MR = \frac{\chi_t - \chi_{eq}}{\chi_0 - \chi_{eq}} = \frac{4}{\beta^2}\exp(-\frac{\beta^2 D_{eff}}{r^2}t) \qquad (5)$$

The values of the diffusion coefficients are respectively $18,52.10^{-10} m^2 s^{-1}$; $17,84.10^{-10} m^2 s^{-1}$ and $17,96.10^{-10} m^2 s^{-1}$ for the okra spread on racks 1 to 3.Table 3 compares the value of the diffusion coefficient obtained with that in the literature.

CONCLUSION

At the end of this study, we carried out vacuum studies in order to evaluate the thermal performance of the dryer. The maximum temperature values recorded for the concrete, the air at the inlet and the air at the outlet of the drying chamber are respectively 47.6°C; 52.2°C; 43.5°C with solar irradiation of 1000W/m^2. At the level of the three racks, the temperatures are between 43.3°C and 44.7°C.The initial mass of okra per rack being, during drying the masses of okra increased from 1500g to 153g, 148g and 150g respectively for racks 1, 2, and 3, i.e. a loss of water between 1347g and 1352g. The final water contents of okra are respectively 0.085 kg of water/kg of dry matter, 0.057 kg of water/kg of dry matter, and 0.079 kg of water/kg of dry matter for okra from rack1, rack 2 and rack 3.

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