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A COMPARATIVE STUDY OF DIRECT AND INDIRECT SOLAR DRYING OF MANGO

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ABSTRACT

In this work, direct and indirect solar drying parameters of two mango varieties were estimated and compared using direct and indirect solar dryers under the same meteorological conditions. For both drying methods, drying curves were established and fitted using 10 semi-empirical models, drying rate and drying efficiency curves were determined, effective water diffusivity was estimated and quality of dry slice was evaluated. Results showed that in indirect solar drying, the tray position in the dryer did not have an influence on drying curves whereas in direct solar drying this influence was very significant. Indirect solar drying curves were suitably fitted by Approximation diffusion model (with $R^2 \approx 0.99$, RMSE≈0.0387, E<12 % and $\chi^2 < 10^{-5}$) while direct drying curves were best fitted by Verma and al. and Approximation diffusion models (with $R^2 \approx 0.99$, RMSE<0.0276, E<12 % and $\chi^2 < 10^{-3}$). Indirect solar drying offered highest drying rates and water diffusivities. Its diffusivities increased with the number of drying days between 1.5 $\times 10^{-10}$ and 2 $\times 10^{-10}$ m²/s whereas those of direct solar drying decreased with the drying days number between 5 $\times 10^{-11}$ and 1.85 $\times 10^{-10}$ m²/s. With efficiency from 2 to 48 % indirect solar drying was found to be more effective than direct solar drying with efficiency from 0 to 34 %. Indirect solar drying with an average final water content of 16.6 % (dry basis) and a final water activity of 0.57 was then the most efficient, but also the most expensive. Thus, indirect solar dryer was found to be suitable for industrial or semi industrial mango drying, whereas direct solar dryer was appropriate to a family scale traditional mango drying.

KEY WORDS: solar drying, mango, drying curve, drying rate, water diffusivity, drying efficiency

1. INTRODUCTION

According to FAO statistics, more than 300 000 tons of mango are produced each season in West Africa (mainly in Ivory Cost, Burkina Faso, Mali, Senegal and Ghana) (Table1). However, a great proportion (about 150 000 tons) of this production is lost during and after harvests against a very weak proportion exported mainly towards the European Union (Table 1). Thus, from 2003 to 2006, these exports counted for about 6% of the total production and brought more than 60 million US dollars to these countries (Table 1). Mango trading could thus generate enormous financial incomes for these poor countries if the post harvests losses are minimized. To reduce post harvests losses, the drying process is more and more used to preserve a part of the fruit production before its marketing. Also, direct and indirect solar dryings are increasingly adopted because of favourable meteorological conditions of harvests period (high solar radiation, weak relative humidity) and of the high cost of the other energy sources (electricity, gas). Each of these solar drying methods was often studied separately in the literature; however no compararative study was undertaken between their performances and their characteristics. It is this comparative study that we have chosen to present in the current study. Recently, some studies were carried out on solar drying of West Africa mangoes: Dissa et al. (2009) reported a thin layer indirect solar drying model of mango slices with an experimental validation. In Senegal, Rankins, Sathe and Spicer (2008) carried out experiments on solar drying of mango using a greenhouse-type solar dryer. These authors showed that the solar drying of mango could be a means of preservation of an important source of vitamin A for populations of French-Speaking West Africa. During experimental investigation of a solar dryer with natural convective heat flow, Gbaha et al. (2007) studied direct solar drying kinetics of plantain banana, sweet banana, cassava and mango. Koua et al. (2009) carried out a mathematical modelling of thin layer solar drying of banana, mango and cassava using seven statistical semi-empirical models and studied some drying parameters of these products. Touré and Kibangu-Nkembo (2004) reported a comparative study of direct solar drying of cassava, banana and mango. They correlated initial moisture content to the maximum difference between product temperature and ambient air temperature.

The aim of the current study is to compare performances of direct and indirect solar drying parameters for the main mango varieties (*Amelie* and *Brooks*) produced in West Africa. Drying characteristics, namely drying curves, drying rates, water diffusivity and drying efficiency were evaluated for both drying methods and compared. At last, the quality of the dry product obtained from each drying method is investigated through colour measurements and final water activity value.

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Nomenclature

a, b, c	coefficients in drying curve models
a^*	redness index
A_0	albedo
A, B	characteristic coefficients of the sky state
A_{wf}	dry product water activity
b^*	yellowness index
C	solar radiation correction factor due to earth-sun distance variation
d	half thickness of slice (*m*)
db	dry basis
D_{eff}	effective diffusivity (m^2/s),
dm	dry matter
dt	time step (*s*)
E	relative error (*%*)
F_R	collector removal factor
g	coefficient in model of Verma et al.
G	solar radiation (W/m^2)
k, k_0, k_1	coefficients in drying curve models
L^*	lightness index
L_v	latent heat of vaporization ($J\ kg^{-1}$)
m	mass of the product (*kg*)
$\dot{m}_a$	air flow ($kg\ s^{-1}$)
M_e	molar mass of water, M_e =18 $g\ mol^{-1}$
m_e	mass of water in the product (*kg*)
$\dot{m}$	rate of evaporation (*kg/s*)
m_s	dry mass (*kg*)
N	number of observations
P_{ext}	power of the air extractor (*W*)
Q_u	collector useful heat power (*W*)
R	perfect gas constant, *R*=8.3145 $J\ mol^{-1}K^{-1}$
R^2	coefficient of determination
RMSE	root mean square error
S	collector surface area (m^2)
t	drying time (*s*)
T	temperature (*K*, ℃)
U_L	collector overall heat loss coefficient ($W\ m^{-2}\ K^{-1}$)
wb	wet basis
X	water content in dry basis ($kg_{water}/kg_{dry\ matter}$ *db*)
$\dot{X}$	drying rate ($kg\ kg^{-1}\ s$)
y	coefficients in drying curve models
z	number of constants in drying models

Greek letters

β	tilt angle of the collecting surface (*deg*)
χ^2	reduced chi-square
ΔE	colour deviation
ΔH_s	net isosteric heat of sorption (*J/kg*)
Δt	time step between two successive measurements (*s*)
η	efficiency (*%*)
λ	drying constant (s^{-1})
Ψ	moisture ratio

Subscripts

0	initial
a	air
ai	air inlet
amb	ambient air
ao	air outlet
c	collector
cr	critical
d	diffuse
D	direct
dsd	direct solar dryer
eq	equilibrium
f	final
h	horizontal surface
isd	indirect solar dryer
s	dry

Table 1: Estimated annual production, exportation, post harvest loss and exportation financial incomes of mango for five (05) countries of West Africa [a].

Country	Annual production	2000	2001	2002	2003	2004	2005	2006
		Quantity exported towards external market (tons)						
Burkina Faso	71 000 [b]	866	3500	2750	8050	838	1181	2172
Ivory Coast	124 910 [c]	12 038	11051	10471	7761	12091	11113	15374
Ghana	4 000 [c]	244	169	126	193	227	772	369
Mali	61 420 [c]	1 600	900	2152	881	2170	3048	8554
Senegal	61 650 [c]	617	916	1950	2625	3400	3800	6410
Total	322 980	15 365	16536	17449	19510	18726	19914	32879
Exportation proportions		4.76%	5.12%	5.40%	6.04%	5.80%	6.17%	10.18%
		Post harvest loss (tons) [*]						
Burkina Faso		35 067	33750	34125	31475	35081	34909.5	34414
Ivory Coast		56 436	56929.5	57219.5	58574.5	56409.5	56898.5	54768
Ghana		1 878	1915.5	1937	1903.5	1886.5	1614	1815.5
Mali		29 910	30260	29634	30269.5	29625	29186	26433
Senegal		30 516.5	30367	29850	29512.5	29125	28925	27620
Total		153 807.5	153222	152765.5	151735	152127	151533	145050.5
Post harvest proportions		47.62%	47.44%	47.30%	46.98%	47.10%	46.92%	44.91%
		Value of exportation in the same period (10^3 US$)						
Burkina Faso		379.52 [b]	631.81 [b]	1 274.29 [b]	1 678.43 [b]	1 552.07 [b]	1 783.22 [b]	2 717.21 [b]
Ivory Coast		3 335	3 169	3 197	2 691	4 877	5 381	6 969
Ghana		128	70	70	239	689	280	2 074
Mali		500	1 350	622	483	1 171	1 439	3 253
Senegal		176.14	346.83	594.83	1 014.05	1 581.02	1 806.74	3 243.91
Total		4 518.66	5 567.63	5 758.13	6 105.48	9 870.09	10 689.96	18 257.12

[a] Source: (FAO, 2009)
[b] Source: (INSD-BF, 2009)
[c] Source: (FAOSTAT, 2007)
[*] Post harvest loss represented about 50% of non-exported production according to literature estimates (Toure & Kibangu-Nkembo, 2004; Rankins, Sathe & Spicer, 2008)

2. Materials and methods

2.1. Experimental dryers

⇒ *Direct solar dryer*

The direct solar dryer was made of a metal framework of 1.20 m height supporting four rectangular trays of 0.39 m x 1.02 m dimensions (Figure 1a). Trays were made of a wooden frame whose bottom is covered with nylon net to facilitate the air flow through the drying bed. Each of these drying trays had a maximal capacity of 2 kg. The dryer sides were also covered with nylon net in order to prevent any contact between drying product and outside. The last tray located in the upper part of the dryer is exposed to solar radiation. Thus, for this model of dryer, solar radiation is directly used to evaporate product water by radiation heat transfer. Water vapour produced is carried by surrounding air crossing the drying bed. Performances of such a dryer are function of ambient conditions and of solar radiation received on drying site.

⇒ ***Indirect solar dryer***

The indirect solar dryer was made of a solar collector (used to produce thermal energy) coupled with a drying unit (Figure 1b). The solar collector with a rectangular duct had a mixed type absorber resulting from the coupling of a corrugated iron absorber and a porous absorber made of a mesh of aluminium. It converts into heat a part of solar radiation received on its collecting surface. Thus, the air crossing its porous absorber receives a portion of this energy by convective heat exchange. The obtained hot air flows in the drying unit for the drying of mango slices. This drying unit is a wooden enclosure of parallelepiped shape. Its upper part is surmounted of cone shaped roofing carrying to its summit a PVC tube chimney (3). This chimney supports at its base an air extractor (4) of low power (12W) and 64.8 m^3/h airflow. The bottom part of the drying unit is provided with a rectangular opening (5) for the hot air inlet. One of the sides is provided with a swing door for loading and unloading mango slices from the dryer. The bottom side is insulated by two superimposed layers of 5 cm of glass wool and 7 cm of shavings. The whole unit is supported by a metal frame located at 80 cm above the ground (Figure 1b). The products are laid out inside the dryer on four rectangular trays. Each tray is constructed with wooden frames on which is fixed nylon net to facilitate the air flow. The trays are separated of 20 cm from each other. The top tray is at about 40 cm from the roofing base and the lowest at 20 cm from the insulating bottom. Each of these trays has a maximal capacity of 2 kg.

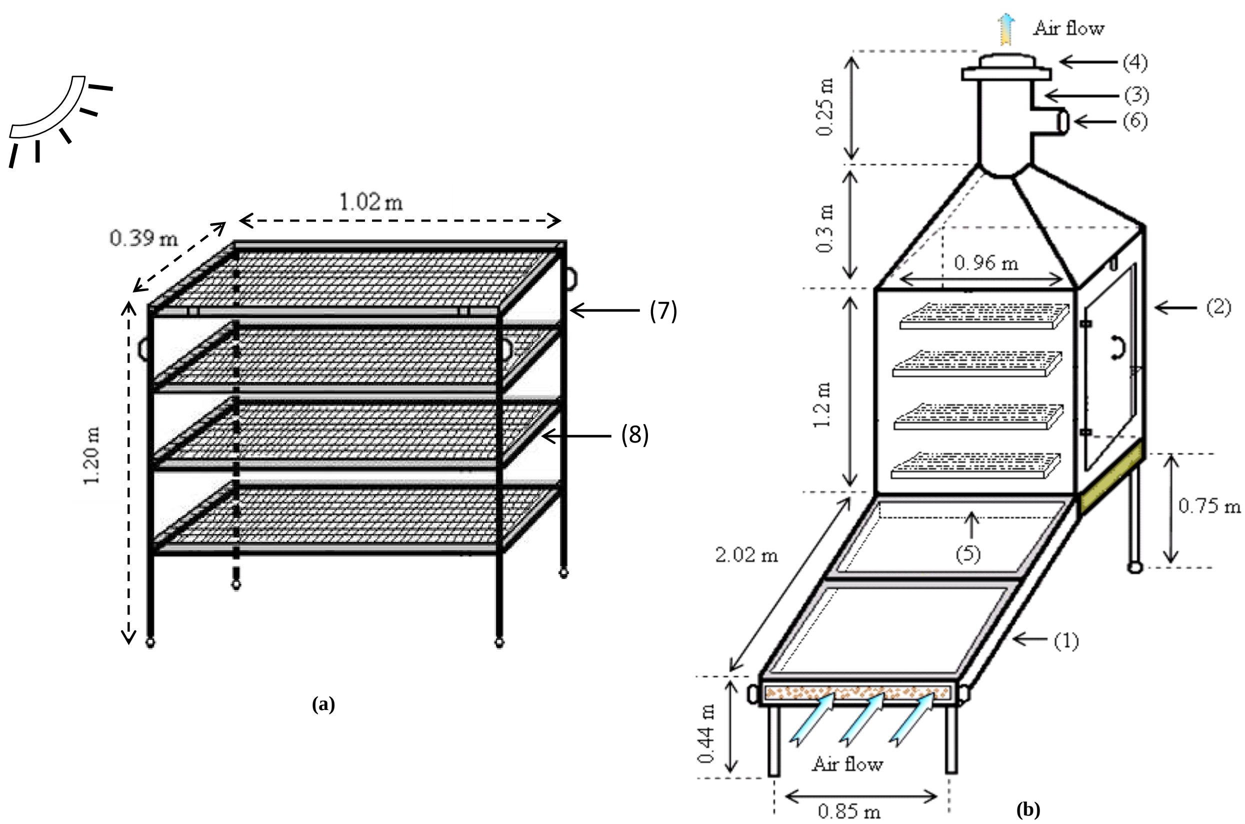


Figure1. Schematic illustration of solar dryers set-up: (a) direct solar dryer (b) indirect solar dryer
Legend:1-Solar collector, 2-Drying unit, 3-PVC chimney, 4- Air extractor 5-Air entrance in drying unit, 6- Air recycling pipe, 7- Frame, 8- Tray

Table 2a: Characteristics of the drying site, of the dryers and of the product

Characteristic of the site	
Wind speed velocity	2.8 m/s
Longitude	12°20-12°26 N
Latitude	1°20-1°36 W
Albedo	0.2 (Daguenet, 1985)
Static pressure	975×10^2 Pa
Solar constant	1353 W/m²
Characteristics of the direct solar dryer	
Collecting surface area	0.19 m²
Number of tray	4
Maximal load	8 kg
Tray surface area	0.19 m²
Dryer load	1.4 kg
Manufacturing cost	85 000 F cfa
Characteristic of the indirect solar dryer	
Collector	
Front collecting surface area (*Glass and corrugated iron sheet*)	1.9 m²
Useful air duct	*Length:*2.02 m *Width:*0.85 m *Equivalent hydraulic diameter* D_h:12.08 cm *Corrugated sheet - back insulation distance:* 6.5 cm
Porous absorber	*Apparent volume :*0.1116 m³ *Porosity* ε *:*0.9
Back insulation	*Wood shavings thickness:*5 cm *Glass wool thickness* :5 cm
Lateral insulation (*Wood*)	3 cm
Metal frame	*Height at the air inlet*: 44 cm *Height at the air outlet*: 75 cm *length* :206 cm *width* :96.5 cm
Collector inclination	8.65°
Drying unit	
Number of tray	4
Dryer initial load	3.2 kg
Maximal load	10 kg
Tray surface area	0.36 m²
Extractor power	12 W
Manufacturing cost	310 000 F cfa
Parameters of the product	
Tray-slice contact rate	0.7
Slice mean dimensions	*Thickness*:0.8 cm *Width*:4 cm *Length*:8 cm
Initial water content	*Amelie*: 6.01db *Brooks*:5.82db

2.2 Mango samples

Mangoes used in this study correspond to *Amelie* and *Brooks* varieties. These two main varieties represent about 50 % of the mango quantity marketed in West Africa and are produced respectively from April to June and from late June to August. For drying operations, good quality fruits were purchased from a local fruit market of Ouagadougou (Burkina Faso), washed and peeled. For each fruit, the flesh was separated from the stone and sliced into samples of 8 mm thick using a stainless steel knife. The slices were then uniformly laid out on trays for solar drying operations.

2.3 Experimental procedure

Direct and indirect solar drying operations were repeated during the same period in April, May and June 2006 and 2008 on the site of the University of Ouagadougou (Ouagadougou, Burkina Faso) located at 12°20-12° 26 N latitude and 1°28-1°36 W longitude. Data of direct solar drying presented in this study are those of 21st, 22nd, 23rd and 24th May, 2008 for *Amelie* variety and of 26th, 27th, 28th and 29th May, 2008 for *Brooks* variety. Likewise, data of indirect solar drying are those of 21st, 22nd and 23rd May, 2006 for *Amelie* variety and of 226th, 27th and 28th May, 2006 for *Brooks* variety. For each drying method, weighing was carried out using an OHAUS balance of *10 kg ± 0.1 g* maximum capacity. A CD11 model indicator connected to this balance allowed direct reading of drying trays mass. For each dryer, the four trays were numbered from 1 to 4 going from the bottom to the top and were weighed before the beginning of each drying operation. For drying, mango slices were uniformly distributed on the four trays occupying about 60 % of their total surface. At the beginning of the drying, each tray of direct and indirect solar dryers carried respectively about 350 g and 800 g of mango flesh. During drying, trays were regularly unloaded and weighed at intervals of time going from 1 hour at the beginning of the process to 2 hours at its end. Characteristics of drying air were also measured in each case. Ambient air and indirect solar drying unit inside temperatures were recorded using a case of K type thermocouples connected to a computer using the temperature acquisition software TESTPOINT (Version 3.4) and their relative humidities were measured using a digital probe thermohygrometer of Bioblock mark of ±3 % precision.

3. Methods of solar drying data processing

3.1. Drying curves and drying rates determination

Mango slices water content was estimated on dry basis. At the end of the drying operations, a sample was taken on each tray, weighed and placed in an oven drying (*MEMMERT)* at 70°C for 24h in order to determine the dry mass (AOAC, 1990). From the dry mass value of these samples, that of the total dry product on each tray was deduced. The water content at each drying stage was then calculated according to:

$$X = \frac{m_e}{m_s} = \frac{m - m_s}{m_s} \qquad (1)$$

where m_e, X, m and m_s are respectively the product water mass, the water content in dry basis, the mass of the product on each tray and the corresponding dry mass.

The drying curves were obtained from the plots of water content versus drying time and the drying rates were deduced from the water content by differentiation according to the following formula:

$$\dot{X} = -\frac{dX}{dt} = \frac{X_t - X_{t+\Delta t}}{\Delta t} \qquad (2)$$

where: $\dot{X}$ is the drying rate and Δt the time between two successive measurements during drying experiment.

3.2. Mathematical modelling of drying kinetics

The thin layer drying curves obtained from direct and indirect solar drying experiments were fitted using 10 mathematical semi-empirical models reported by the literature (Usub et al., 2009; Toğrul & Pehlivan, 2002; Lahsasni et al., 2004; Doymaz, 2005; Yaldýz & Ertekýn, 2001), and presented on Table 2b. Each one of these models gives the evolution of moisture ratio Ψ according to drying time *t* with:

$$\Psi = \frac{X - X_{eq}}{X_0 - X_{eq}} \qquad (3)$$

where: X_0 is the initial water content and X_{eq} the equilibrium water content corresponding to the temperature and the relative humidity of the drying air.

According to Figure 6, the relative humidity and the temperature of the drying air varied a lot during both solar drying methods. Moreover, the equilibrium water contents X_{eq} calculated from the two varieties sorption isotherms were very small compared to $X(t)$ and X_0 for long drying times. Thus, in our study, the moisture ratio Ψ was simplified to X/X_0 instead of $(X\text{-}X_{eq})/(X_0\text{-}X_{eq})$ like in many previous works (Usub et al., 2009; Mahmutoğlu et al., 1996; Diamente and Munro, 1993).

Solar drying Fittings were carried out using a nonlinear regression tool of software MATLAB (version 7.0.1) based on the nonlinear optimization method of Levenberg-Marquardt. The coefficient of determination R^2 was one of the primary criteria used to select the best model to describe direct and indirect solar drying curves of mango slices (Doymaz, 2005; Toğrul & Pehlivan, 2002). In addition to R^2, the various statistical parameters such as: root mean square error (*RMSE*), relative error (*E(%)*) and reduced chi-square (χ^2) were used to determine the quality of fits. These parameters were given by the following relations:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(\Psi_{\exp,i} - \Psi_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{\Psi}_{\exp} - \Psi_{\exp,i}\right)^2} \qquad (4)$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}\left(\Psi_{pre,i} - \Psi_{\exp,i}\right)^2}{N}\right]^{1/2} \qquad (5)$$

$$E(\%) = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|\Psi_{\exp,i} - \Psi_{pre,i}\right|}{\Psi_{\exp,i}} \qquad (6)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\Psi_{\exp,i} - \Psi_{pre,i}\right)^2}{N - z} \qquad (7)$$

where: $\Psi_{exp,i}$ is the *i*th experimental moisture ratio, $\Psi_{pre,i}$ is the *i*th predicted moisture ratio, $\overline{\Psi}_{\exp}$ the mean experimental moisture ratio, *N* the number of observations, and *z* the number of constants in models.

Thus, the goodness of fits was expressed by higher values of R^2 and lower values of *RMSE*, E (%) and χ^2.

Table 2b: Basic mathematical models usually used for drying kinetics fitting

Model no.	Model name	Model equation	References
1	Lewis	$\Psi = \exp(-kt)$	Ayensu (1997)
2	Henderson and Pabis	$\Psi = a\exp(-bt)$	Mahmutoğlu et al. (1996)
3	Page	$\Psi = \exp(-kt^{y})$	Basunia and Abe (2001)
4	Modified Page	$\Psi = \exp(-(kt)^{y})$	Toğrul and Pehlivan (2002)
5	Logarithmic	$\Psi = a\exp(-kt) + c$	Yaldiz et al. (2001)
6	Two-term model	$\Psi = a\exp(-k_0 t) + b\exp(-k_1 t)$	Lahsasni et al. (2004)
7	Two-term exponential	$\Psi = a\exp(-k_0 t) + (1-a)\exp(-k_0 at)$	Midilli and Kucuk (2003)
8	Verma et al.	$\Psi = a\exp(-kt) + (1-a)\exp(-gt)$	Doymaz (2005)
9	Approximation of diffusion	$\Psi = a\exp(-k_0 t) + (1-a)\exp(-k_0 bt)$	Usub et al. (2009)
10	Wang and Singh	$\Psi = 1 + at + bt^2$	Usub et al. (2009)

3.3. Water effective diffusivity determination

Effective moisture diffusivity of mango slices was estimated from analytical solution of Fick's diffusion equation. Assuming one-dimensional moisture transfers, uniform initial moisture distribution, non-shrinking mango slices and constant moisture diffusivity, this analytical solution of Fick's equation is stated as (Cranck, 1975):

$$\Psi = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[-\frac{(2i+1)^2\pi^2 D_{eff}\,t}{4d^2}\right] \qquad (8)$$

where: D_{eff} is the effective moisture diffusivity, t the drying time, d the half thickness of slices and i the Fourier's series number.

For long drying times (corresponding to $\Psi \le 0.8$ in our case), Equation 8 is almost equal to the first term of Fourier series and becomes (Usub et al., 2009; Lahsasni et al., 2004; Toğrul and Pehlivan, 2002; Doymaz, 2005) :

$$\Psi = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\,t}{4d^2}\right) \qquad (9)$$

From Equation 9 the natural logarithm of Ψ is stated as:

$$\ln(\Psi) = \ln\frac{8}{\pi^2} - \lambda\, t \qquad (10)$$

where: $\lambda = \frac{\pi^2 D_{eff}}{4d^2}$

The plot of natural logarithm of moisture ratio versus drying time obtained from Equation 10 showed an almost linear profile for each drying day. Diffusivity was thus estimated at 1st, 2nd, 3rd and 4th drying day from the slope λ of this straight line according to:

$$D_{eff} = \frac{4d^2\lambda}{\pi^2} \qquad (11)$$

The influence of drying method on the value of mango slices effective diffusivity was then illustrated for each drying day and for each variety.

3.4. Dry product quality assessment

⇒ ***Water activity***

Water activity of dry product is an important parameter for its microbiological stability during storage. The water activity of the dry mango slice was estimated from its equilibrium water content according to the following equation (Dissa et al., 2008, Dissa, 2007):

Amelie:

$$A_{wf} = 1 - \exp\left[-0.0193(T + 44.36)X_{eq}^{0.3316}\right] \qquad (12a)$$

Brooks:

$$A_{wf} = 1 - \exp\left[-0.0194(T + 31.81)X_{eq}^{0.3247}\right] \qquad (12b)$$

where: A_{wf} is the water activity of the dry product, and X_{eq} and T respectively its equilibrium water content and temperature.

⇒ ***Slices colour***

Drying can affect the quality of mango slices because of some chemical reactions intervening during the process. These chemical reactions induce changes in the fruit flesh apparent colour (browning), which lead to a significant colour difference between fresh and dry slices (Figure 13). Apparent quality of direct and indirect solar dried mango slices was thus estimated by determining the colour deviation between fresh and dried slices. Mango slices colour was measured with a spectrophotometer DR LANGE LDC 20-II using the CIE Lab colour space (Hutchings, 1999). Samples colour was thus determined by their lightness L^* (from 0 for black to 100 for perfect white), redness a^* (from +60 for red to -60 for green) and yellowness b^* (from +60 for yellow to -60 for blue). For both drying methods, five samples were identified and 10 colour measurements were carried out on each sample. The browning induced by each drying method was then characterized by the increase in the redness (Krokida & Maroulis, 2000; Maskan, 2001) and by the colour difference between dry and fresh slices evaluated by the colour deviation as (Young & Whittle, 1985):

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (13)$$

where: ΔL, Δa and Δb are respectively lightness, redness and yellowness deviations between dry and fresh slices.

3.4 Drying efficiency

3.4.1 Direct solar drying

The direct solar drying efficiency was expressed by the ratio of the energy used to remove water from the product and the total solar radiation received on the collecting surface as:

$$\eta_{dsd} = \frac{\dot{m}_e \Delta H_s + Q_{ev}}{SG} \quad (14)$$

Hence:

$$\eta_{dsd} = \frac{m_s \dot{X} (L_v + \Delta H_s)}{SG} \quad (15)$$

where $\dot{m}_e$ is the rate of evaporation, m_s the dry mass of the dryer load, S the collecting surface area, $\dot{X}$ the drying rate and G the global radiation given in appendix. ΔH_s is the isosteric heat of desorption related to water molecules desorption at any moisture content X and given by Clausius-Clapeyron equation (Basu, Shivhare, Mujumdar, 2006):

$$\Delta H_s = \frac{R}{M_e}\left[\frac{\partial(\ln A_w)}{\partial(1/T)}\right]_X$$

(16)

where T is the drying temperature, R the perfect gas constant, M_e the mass molar of water, A_w the product water activity given by Equation 12.

L_v is the latent heat of vaporization calculated from the following formula (Jannot & Coulibaly, 1998):

$$L_v = 10^3 (52501.8 - 2.378T)$$

(17)

3.4.2 Indirect solar dryer

⇒ Thermal performances

The indirect solar dryer performances depend on its collector thermal performances illustrated in this study by the collector overall efficiency η_c and its useful power Q_u defined by:

- Collector efficiency (Duffie and Beckman, 1974):

$$\eta_C = F_R\left[(\tau\alpha) - U_L \frac{T_{ai} - T_{amb}}{G}\right] \quad (18)$$

- Collector useful power (Abu-Hamdeh, 2003):

$$Q_u = \dot{m}_a c_a (T_{ao} - T_{ai}) = \eta_c SG \quad (19)$$

where F_R is the collector removal factor, $(\tau\alpha)$ the transmittance-absorptance product of collector, U_L the overall heat loss coefficient of the collector, T_{ai} and T_{ao} respectively the mean temperature of air at outlet and inlet of the collector, T_{amb} the ambient temperature, S the total collecting surface area, c_a specific heat of air and $\dot{m}_a$ the air flow.

⇒ **Dryer efficiency**

The indirect solar dryer efficiency was then expressed by the ratio of the energy required to remove the moisture from the product and the total energy supplied to the dryer (solar radiation + extractor power) according to:

$$\eta_{isd} = \frac{\dot{m}_e (L_v + \Delta H_s)}{SG + P_{ext}} = \frac{m_s \dot{X} (L_v + \Delta H_s)}{SG + P_{ext}} \quad (20)$$

where: P_{ext} is air extractor power.

4. Results and discussion

4.1 Solar radiation

The solar radiation falling on a horizontal plan of the drying operations site (located at 12°20-12° 26 N latitude and 1°28-1°36 W longitude) was calculated for the typical days of mango production months (April 15th, May 15th and June 11th). The daily evolutions of global, direct and diffuse radiation according to hours of the day for these typical days were presented in Figure 4. For the whole period, the theoretical duration of insolation obtained was about 12 hours and the direct, diffuse and global radiations reached simultaneously their maxima at solar midday (12:00). The diffuse radiation curve was almost the same for the three months and showed an almost constant maximum value of 330 *W/m²* between 9:00 and 15:00. For the whole period from April to June, direct and global radiations kept almost the same values at times of the day ranging from 6:00 to 9:00 and from 15:00 to 18:00. For times ranging between 9:00 and 15:00, these radiations varied slightly with the month in relation with the hour of the day. Thus, at solar midday (12:00) of April, May and June, the direct radiation reached respectively 549, 523, 502 *W/m²* whereas global radiation was about respectively 894, 862, 838 *W/m²*. These values of global radiation at 12:00 of typical days of April, May and June were very close to 869, 842 and 831, those reported by Jannot and Coulibaly (1997) for a horizontal plane of Ouagadougou. These high values of solar radiation and insolation duration proved that ambient conditions of mango harvest period are favourable for solar drying operations.

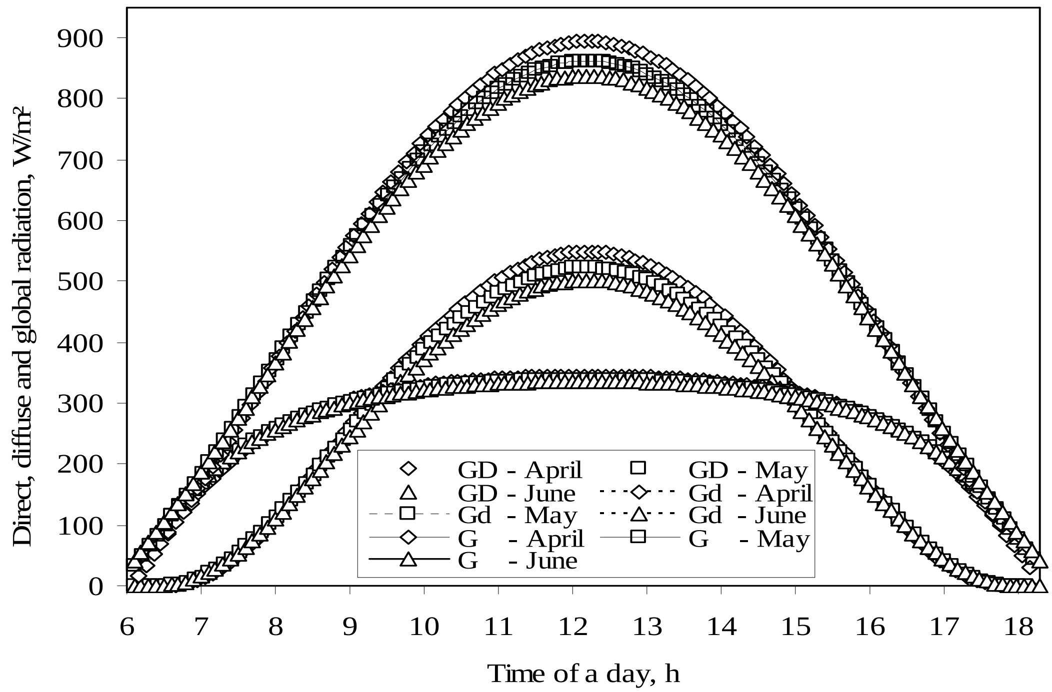


Figure 4: Direct, diffuse and global radiations according to drying hour for typical days of April, May and June months

4.2 Thermal performances of dryers

4.2.1 Direct solar dryer

Thermal performances of the direct solar dryer depend on the evaporating power of ambient air through its ambient temperature and its relative humidity. Thus, changes in temperature and relative humidity of ambient air according to hour of the day for three successive direct solar drying days were illustrated in Figure 6. During this drying period, relative humidity of ambient air oscillated between 35 and 65 % at the 1st day, 40 and 60 % at the 2nd day, and 30 and 65 % at the 3rd day 30 and 66 % while ambient temperature varied between 30 and 33 °C at the 1st day, 30 and 33 °C at the 2nd day, and 31 and 34 °C at the 3rd day. According to Equation 12, these values of ambient air characteristics correspond to equilibrium water content ranging from 1 to 26 % for *Amelie* mango and from 2 to 44 % for *Brooks* mangoes. These ranges of equilibrium water contents were close to the range of mango preservation water contents reported by the literature (Koua et al., 2009, Touré & Kibangu-Nkembo, 2004). From these results, we can deduce that meteorological conditions of this period of mango harvest allow direct solar drying operations of this fruit.

4.2.2 ***Indirect solar dryer***

Thermal performances of the indirect solar dryer depend on those of the solar collector (given by the thermal efficiency and the useful heat power) and the evaporating power of air in the drying unit.

Evolution of the solar collector thermal efficiency and useful heat power for typical days of April, May and June were given in Figure 5. These data showed that the drying air received a useful heat from solar collector during only 9 hours of the day ranging between 7:30 and 16:30. Consequently, the indirect solar drying time of mango slices should be evaluated by considering this interval of day hours. From Figure 5, one can notice that the efficiency and the useful power of collector slightly varied according to the month in relation with the hour of the day. This variation increased when we tended toward solar midday. These performances of the solar collector reached their maximal values at solar midday (12:00). At this hour of the day, the global efficiency and the useful power reached respectively about 35 % and 300 *W/m²* on the whole period from April to June. This maximal efficiency of our collector was higher than those of Madhlopa, Jones & Kalenga (2002) which were about 21.3 % and 17 % respectively for a wire mesh absorber and a fixed wooden absorber plate (with G=865 W/m^2, $30 \le T_{amb} \le 36$ °C et $\dot{m}_a = 0.023\,kg/s$, V_w=2.8 m/s). This efficiency was also higher than those obtained by Ayensu (1997) for a solar dryer with convective heat flow (η_c=21.0 %), Goyal & Tiwari (1997) for a reverse flat plate absorber cabinet (η_c =13.0 % to 19 %), and Belghit et al. (1997) a solar dryer in forced convection (G=900 W/m^2, η_c=18 %).

Temperature and relative humidity curves of air in drying unit for the three indirect solar drying days were presented in Figure 6. According to this figure, relative humidity of drying air ranged respectively from 25 to 55 % at the 1st day, from 27 to 50% at the 2nd day, and from 15 to 50 % at the 3rd day. Also, temperature in the drying unit varied in the range 33-45 °C at the 1st day, 32-50°C at the 2nd day, and 37-63 °C at the 3rd day. According to Equation 12, these values of drying air parameters correspond to equilibrium water content lower than 1.3 % for *Amelie* variety and 2 % for *Brooks* variety. Considering above thermal performances, we can deduce that our indirect solar dryer could ensure drying operations of mango by taking into account drying days' insolation duration. In practice, these performances should also depend on the meteorological variations.

For the same hour of day, one can thus notice that in the indirect solar dryer unit, the relative humidity decreased with the number of drying day and the temperature increased with this one; while in ambient medium, curves of these physical parameters did not change significantly from a drying day to another.

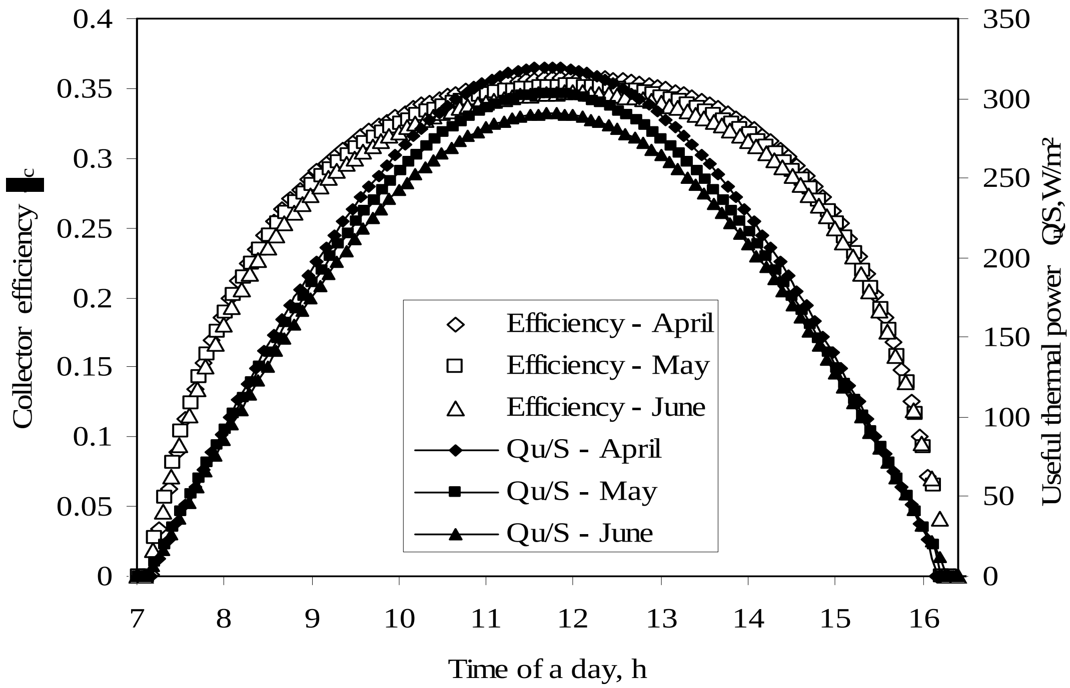


Figure 5. Efficiency and useful thermal power of indirect solar dryer collector according to drying hours for typical days of April, May and June

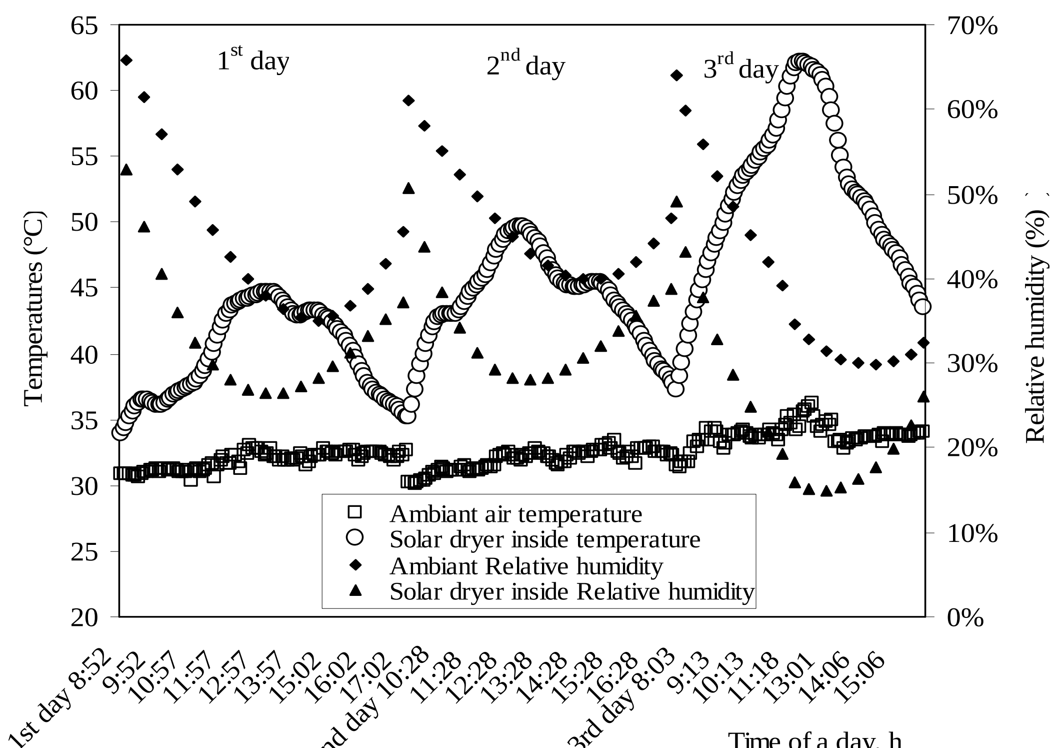


Figure 6: Temperature and relative humidity of ambient air and indirect solar drying air during three successive drying days (1st day: mean values of 21 and 26 May, 2nd day: mean values of 22 and 27 May, 3rd day: mean values of 23 and 28 May)

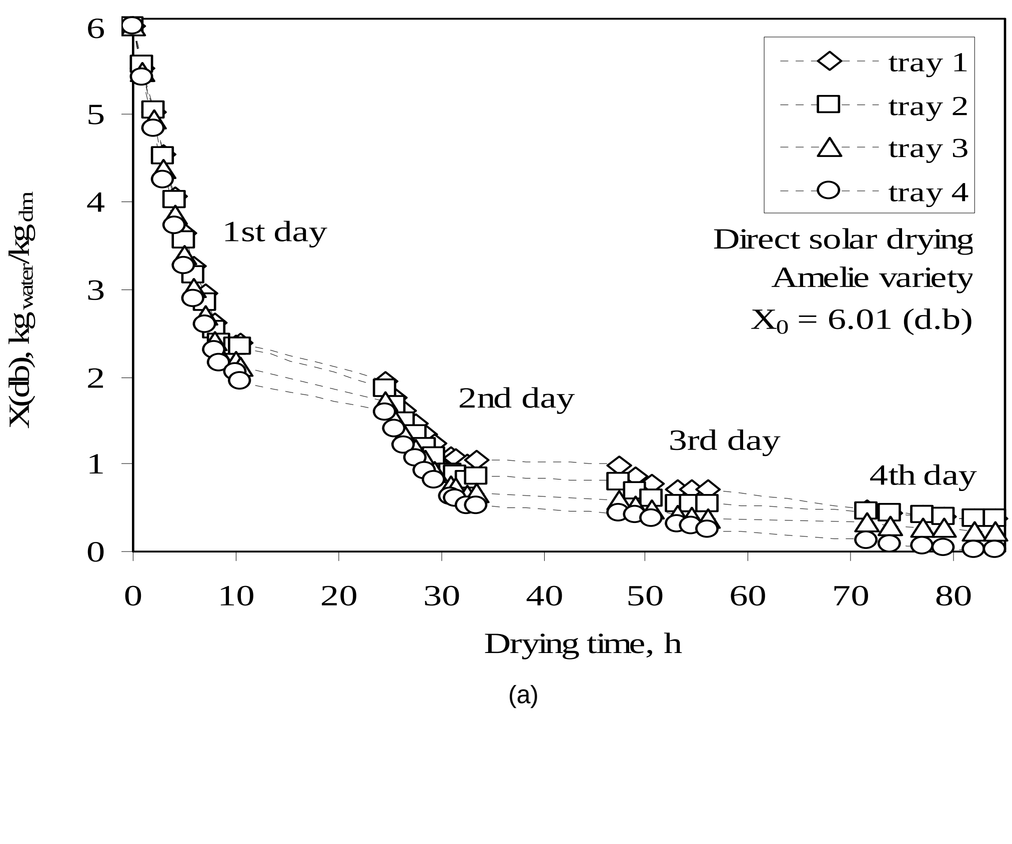
4.3 Influence of solar drying method on drying parameters

4.3.1 Influence on drying kinetics

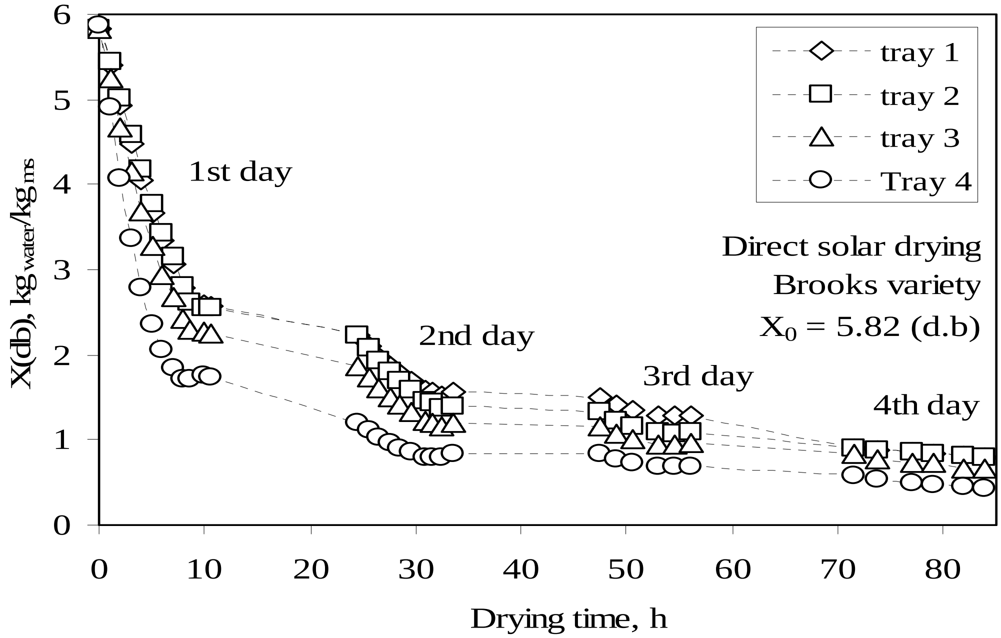
Direct and indirect drying curves of *Amelie* and *Brooks* mango varieties per drying tray were presented on Figures 7a&b and Figures 8a&b. Each dryer had 4 trays numbered from 1 to 4 from the bottom to the top of the drying unit. At the beginning of drying, each one of these trays was loaded with about 800 g and 350 g of fresh mango respectively in indirect solar drying and in direct solar drying.

In direct solar drying, the drying was carried out in four days. Mango slices water content at the end of the 1st day on the 1st, 2nd, 3rd and the 4th tray was respectively 0.39 X_0, 0.39 X_0, 0.35 X_0 and 0.32 X_0 for *Amelie* variety and 0.44 X_0, 0.44 X_0, 0.39 X_0 and 0.30 X_0 for *Brooks* variety (Figures 7a&b). These water contents per drying tray were respectively 0.17 X_0, 0.14 X_0, 0.11 X_0, and 0.09 X_0 at the end of the 2nd day and 0.12 X_0, 0.09 X_0, 0.06 X_0, and 0.04 X_0 at the end of 3rd day for *Amelie*; and 0.27 X_0, 0.24 X_0, 0.21 X_0, and 0.14 X_0 at the end of the 2nd day and 0.22 X_0, 0.19 X_0, 0.16 X_0, and 0.12 X_0 at the end of 3rd day for *Brooks* (Figures 7a&b). At the end of drying, the product water content (in dry basis) on the 1st, 2nd, 3rd and 4th tray was respectively 37.27 %, 37.01 %, 22.60 % and 2.47 % for *Amelie* and 78.85 %, 78.73 %, 88.58 % and 41.93 % for *Brooks* (Figures 7a&b). For this drying method, we can easily notice that at each instant of drying, water content depended on the drying tray position in the dryer and this tendency was considerable from the beginning until the end of the drying process. Thus, these results showed that the tray position in the dryer has a significant influence on direct solar drying kinetics of mango slices.

In indirect solar drying, the water content at the end of the 1st day on the 1st, 2nd, 3rd and the 4th tray was respectively 0.43 X_0, 0.51 X_0, 0.56 X_0 and 0.56 X_0 for *Amelie* variety and 0.41 X_0, 0.38 X_0, 0.57 X_0 and 0.48 X_0 for the *Brooks* variety. At the end of the 2nd day, these water contents were about 0.14 X_0, 0.16 X_0, 0.18 X_0 and 0.17 X_0 for *Amelie* variety and 0.10 X_0, 0.10 X_0, 0.14 X_0 and 0.10 X_0 for *Brooks* variety (Figures 8a&b). From these results, it can be deduced that about 82 to 90 % of mango slices moisture was removed after two drying days and that there are not significant differences between drying curves of different trays during these drying days. At the 3rd day, trays drying curves were very close and were more and more confused when we tend towards the drying end. Final water contents (in dry basis) on 1st, 2nd, 3rd and 4th tray were respectively 16.25 %, 15.04 %, 17.45 % and 18.05 % for *Amelie* variety and 15.51 %, 16.37 %, 17.27 % and 17.18 % for *Brooks* variety. Thus, we can deduce that in indirect solar drying, the tray position in the dryer does not influence enough drying curves and that a large proportion of the product moisture is removed at the 1st and 2nd drying days. This behavior of indirect solar drying of mango is similar to that found by Desmorieux et al. (2008) for convective drying of mango in a semi-industrial dryer. These authors obtained by simulation that in convective drying of mango (with gas as source of energy), tray position in the dryer did not have enough influence on drying kinetic until the 12th tray.

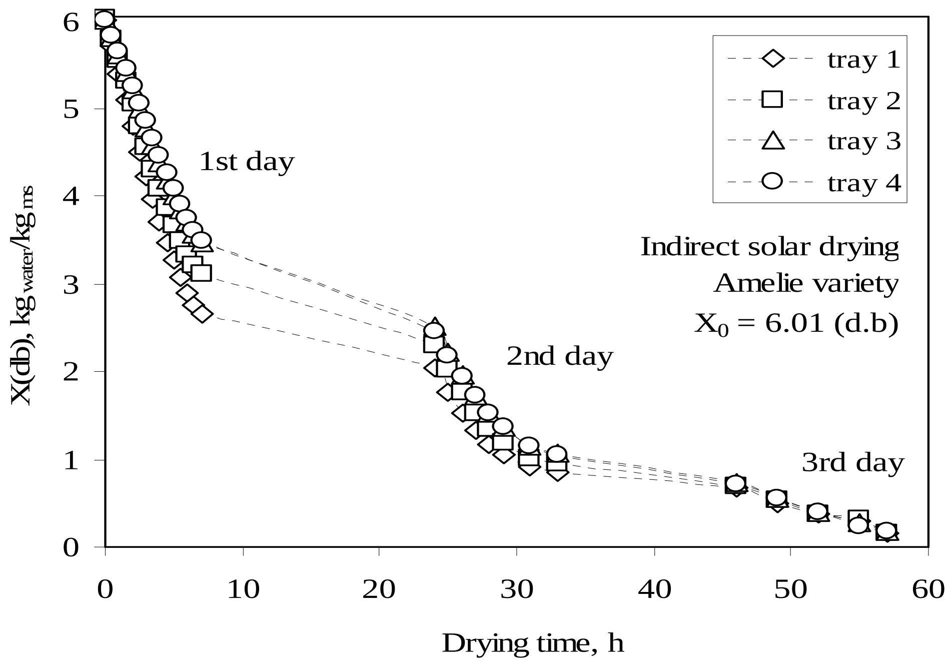


(a)

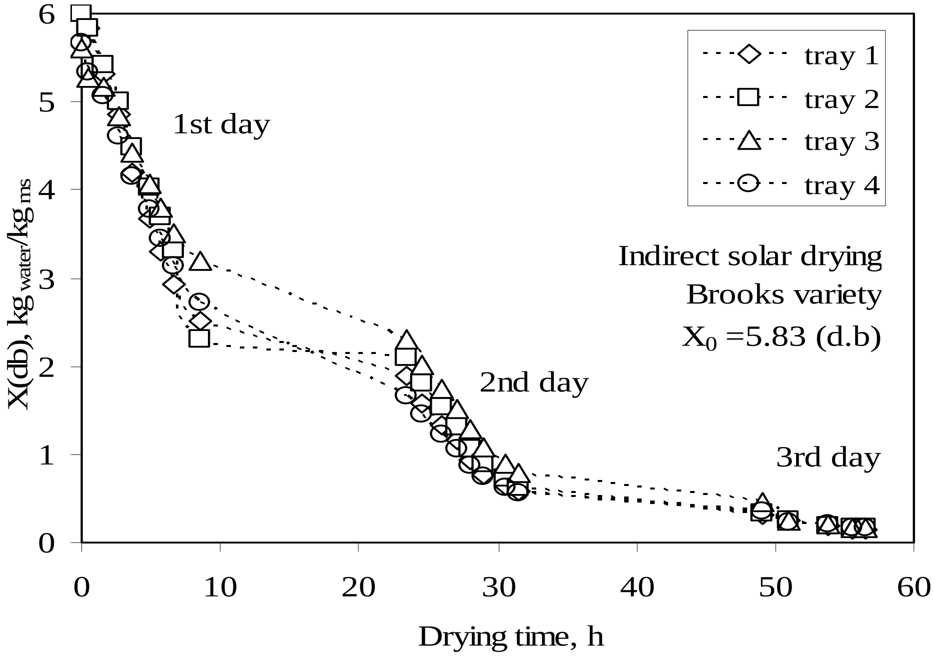


(b)

Figure 7. Direct solar drying kinetics of mango for a four-trays dryer: (a) *Amelie* variety (b) *Brooks* variety



(a)



(b)

Figure 8: Indirect solar drying kinetics of mango for a four-trays dryer: (a) *Amelie* variety (b) *Brooks* variety

In order to illustrate the influence of the drying method on solar drying curves of mango, we considered the average water content of the four trays of each dryer. The plots of moisture ratio according to solar drying time of *Amelie* and *Brooks* mango varieties for both drying methods were presented in Figure 9.

In direct solar drying, at the end of the 1st, 2nd, 3rd and 4th drying day, the average residual water contents were respectively close to 0.37 X_0, 0.13 X_0, 0.08 X_0 and 0.04 X_0 for *Amelie* and 0.39 X_0, 0.21 X_0, 0.17 X_0 and 0.16 X_0 for *Brooks*. According to Figure 9, the two varieties had distinct drying curves and it was found that *Amelie* dried more quickly than *Brooks*. The final water content of the product (in dry basis) was thus close to 24.83 % for *Amelie* variety and 66.31 % for *Brooks* variety (Table 6). The final water content of *Brooks* was widely higher that given by almost all the previous studies, while the final water content of *Amelie* was close to 27.6 % wb (38 % db) that found by Touré and Kibangu-Nkembo (2004) when comparing direct solar drying of cassava, banana and mango and was in the range 15-20 % wb (i.e.18-25 % db) reported by Gomez (1981) for direct solar drying of mango slices of 1.5 cm thick. From these data, we can deduce that the type of variety has a significant influence on direct solar drying curves of mango and *Amelie* should be considered as a suitable variety for direct solar drying.

In indirect solar drying, the average residual water contents at the end of the 1st, 2nd and 3rd drying days were respectively about 0.52 X_0 0.16 X_0 and 0.03 X_0 for *Amelie* variety and 0.46 X_0, 0.11 X_0, and 0.03 X_0 for *Brooks* variety. According to Figure 9 and Table 6, the two varieties had indirect solar drying curves very close and had almost the same final water contents of about 16.60 % db (14.24% wb) for *Amelie* and 16.68 % (14.30% wb) for *Brooks*. These final water contents of mango varieties were close to 13 % wb that obtained by Gbaha et al. (2007) and were in the range 12-20 % wb of previous work reported by Touré and Kibangu-Nkembo (2004). They were also lower than 18% wb the typical water content of the dried fruits given by Coultate (1996). From these results, we can then deduce that the type of variety does not have a significant influence on indirect solar drying curves of mango.

At the first drying day (corresponding partially to the period of unbound water evacuation), direct solar drying seemed as efficient as indirect solar drying with drying kinetics relatively close to those of indirect solar drying (Figure 9). The direct solar drying performances strongly decreased as we tended towards the last stages of drying. The effectiveness of indirect solar drying was clearly observable from the second drying day where the indirect solar drying curves showed very high slopes compared to direct solar drying curves (Figure 9). To have a good quality dry product, direct solar drying required a fourth drying day. But, the average final water content obtained after this 4th day remained higher than that of indirect solar drying. Thus, in three drying days, the indirect solar drying allowed to have an average final water content of 16.6 % db that the direct solar drying did not allow to have even in four drying days. These results can be explained by the fact that the indirect solar drying is carried out at the highest temperatures. Relative humidities of drying air are then the lowest and the product equilibrium water contents are thus weaker than those of direct solar drying (which is carried out in ambient air).

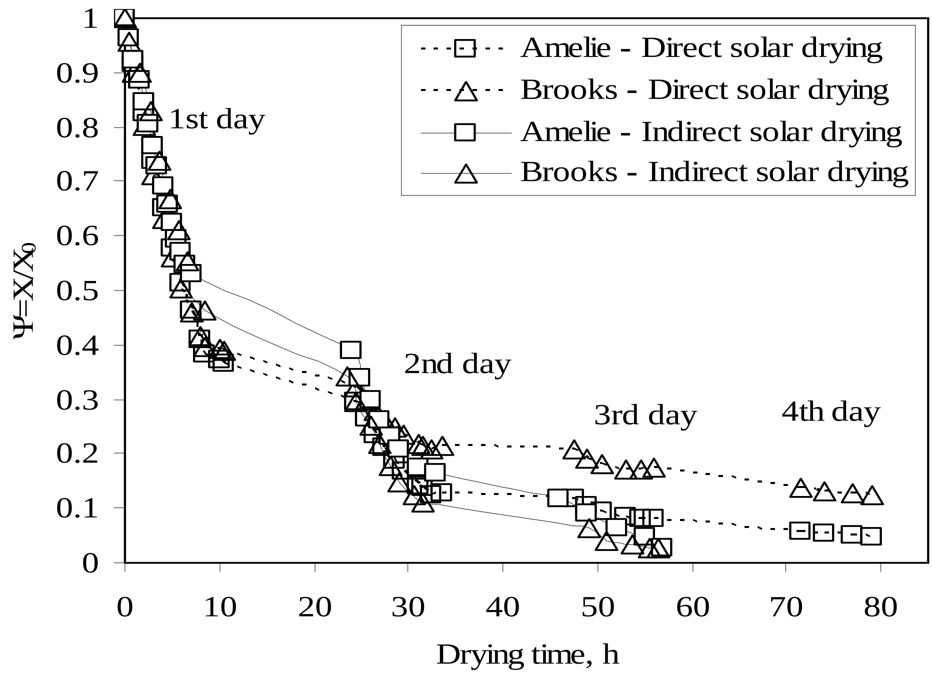


Figure 9. Comparison of direct and indirect solar drying kinetics *Amelie* and *Brooks* mango varieties

4.3.2 Influence on drying rates

For each drying method, drying rates were estimated from the average water contents of the four trays. Direct and indirect solar drying rates curves obtained were presented in Figure 10. For both drying methods, curves of Figure 10 showed a short constant-rate drying period at the beginning of the 1st drying day and a very long falling-rate drying period for the rest of the drying duration. Falling-rate drying periods were delimited from short constant-rate periods by critical water contents evaluated by tangents method and presented on Table 6.

At the 1st drying day, drying rates of *Amelie* and *Brooks* mango varieties reached respectively maxima of 0.18 $g\ kg^{-1}\ s^{-1}$ and 0.14 $g\ kg^{-1}s^{-1}$ in direct solar drying, and of 0.15 $g\ kg^{-1}s^{-1}$ and 0.16 $g\ kg^{-1}s^{-1}$ in indirect solar drying. At this 1st drying day, we notice that the direct solar drying seemed as effective as indirect solar drying with drying rates relatively close to those of indirect solar drying (Figure 10). At the 2nd and the 3rd drying days, direct solar drying showed drying rates relatively very low compared to those of indirect solar drying. At the 2nd day, direct solar drying rates had a maximum value close to 0.04 $g\ kg^{-1}s^{-1}$ for both varieties while indirect solar drying rates reached maxima of 0.12 $g\ kg^{-1}s^{-1}$ and 00.11 $g\ kg^{-1}s^{-1}$ respectively for *Amelie* and *Brooks* varieties. At the 3rd day, both varieties had very weak direct solar drying rates lower than 0.015 $g\ kg^{-1}s^{-1}$ and indirect solar drying rates reaching 0.04 $g\ kg^{-1}s^{-1}$ and 0.055 $g\ kg^{-1}s^{-1}$ respectively for *Amelie* and *Brooks*. From these results, we can deduce that most of direct and indirect solar dryings of *Amelie* and *Brooks* mango varieties takes place during the falling-rate drying phase and that the direct solar drying shows very low drying rates compared to indirect solar drying for most of solar drying process. Analogous behaviour was observed during convective drying of *Amelie* mango by Dissa, Desmorieux, Bathiebo and Koulidiati (2008) and of okra by Doymaz (2005).

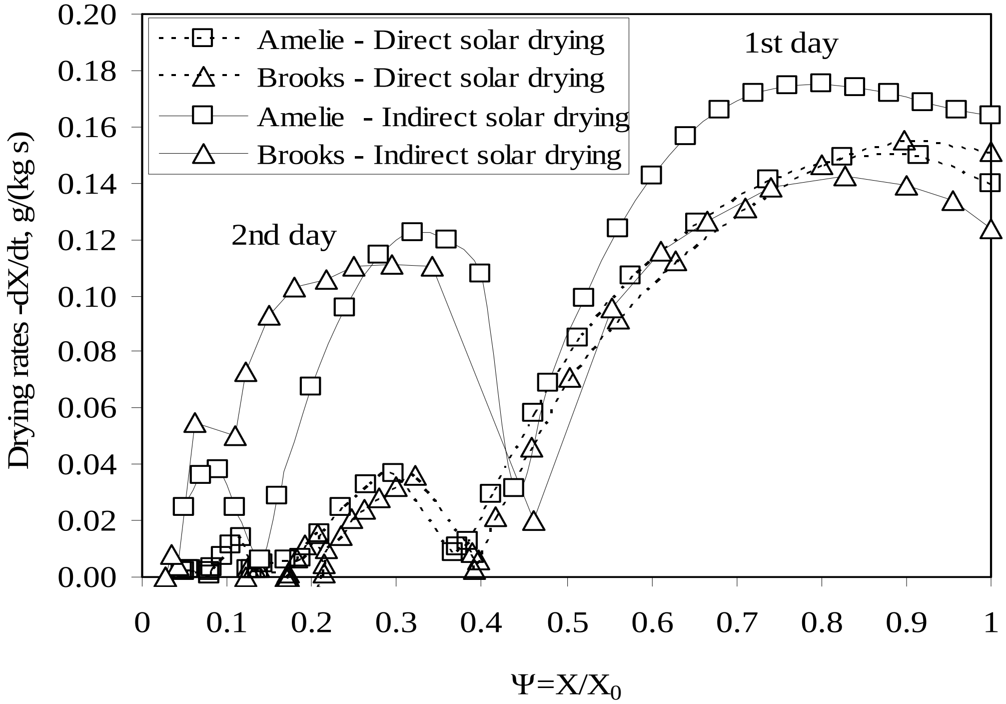


Figure 10. Comparison of direct and indirect solar drying rates of *Amelie* and *Brooks* mangoes

4.3.3 Influence on product drying kinetics model

Direct and indirect solar drying curves symbolized by the plots of moisture ratio Ψ vs. drying time *t* were fitted using the 10 semi-empirical models of Table 2b. For each variety and for each drying method, the regressions were carried out using average values of Ψ according to drying time (Figure 9). The regressions statistics were shown on Table 3 for indirect solar drying and on Table 4 for direct solar drying.

In indirect solar drying, statistics of Table 3 showed that for both mango varieties, “Approximation of diffusion” model (corresponding to model No.9) had the highest values of R^2 and the lowest values of RMSE, E and χ^2 (with $R^2 \approx 0.99$, RMSE≈0.0387, E≤11.1929% and $\chi^2 \leq 9.9479 \times 10^{-6}$). With the best values of fitting parameters, this model may be assumed to represent indirect solar drying curves of mango varieties.

In direct solar drying, statistics of Table 4 showed that “Approximation of diffusion” and “Verma and al.” models (corresponding to model No.8 and 9) had the highest values of R^2 and the lowest values of RMSE, E and χ^2 (with $R^2 \approx 0.99$, RMSE≤0.0276, E≤11.0031% and $\chi^2 \leq 7.6351 \times 10^{-4}$). Moreover, fitting parameters values of the two models were very close. So, these models may be assumed to describe direct solar drying curves of both mango varieties.

For both drying methods, the suitability of “Approximation of diffusion” model is due to the fact that most of direct and indirect solar drying of mango slices takes place at falling-rate drying period dominated by the water diffusion mechanism. This shows that water diffusivity coefficient is a significant characteristic that should be identified for direct and indirect solar drying of mango.

Table 3. Modelling of Ψ vs. *t*(h) for indirect solar drying of *Amelie* and *Brooks* mangoes slices

Models no.	Parameters				R^2	RMSE	E(%)	χ^2
				Amelie				
1	k=0.0606				0.9346	0.0789	18.6822	0.0092
2	a=0.9242	b=0.0539			0.9586	0.0628	13.7316	1.3764×10^{-4}
3	k=0.1203	y=0.7735			0.9781	0.0456	15.9999	0.0013
4	k=0.0647	y=0.7735			0.9781	0.0456	16.0029	0.0013
5	a=0.895	k=0.0701	c=0.0577		0.9616	0.0604	22.6125	8.7040×10^{-5}
6	a=0.3127	k_0=0.2991	b=0.7085	k_1=0.0428	0.9846	0.0383	13.9273	0.0012
7	a=0.1914	k_0=0.2585			0.9732	0.0505	12.8152	3.4182×10^{-4}
8	a=0.7045	k=0.0427	g=0.2726		0.9838	0.0393	14.1454	0.0018
9	a=0.3124	b=0.1334	k_0=0.2882		**0.9858**	**0.0387**	**10.2171**	**1.2609×10^{-6}**
10	a=-0.0416	b=0.0005			0.9366	0.0885	86.2301	0.2558
				Brooks				
1	k=0.0744				0.9653	0.0609	24.6398	0.0123
2	a=0.9771	b=0.0709			0.9699	0.0567	20.8744	0.0122
3	k=0.0963	y=0.893			0.9786	0.0479	11.5589	0.0071

4	k=0.0728	y=0.893			0.9785	0.0479	11.5677	0.0072
5	a=0.9542	k=0.0851	c=0.0454		0.9703	0.0563	23.6396	0.0082
6	a=0.5373	k_0=0.1307	b=0.4755	k_1=0.0448	0.9781	0.0484	15.4199	0.0068
7	a=0.3519	k_0=0.1509			0.9792	0.0472	12.3483	0.0069
8	a=0.5669	k=0.1193	g=0.0432		0.9779	0.0486	15.5178	0.0073
9	a=0.2417	b=0.1927	k_0=0.2558		**0.9860**	**0.0387**	**11.1929**	**9.9479x10^{-6}**
10	a=-0.0469	b=0.0005			0.8789	0.1138	95.7371	0.0270

Table 4. Modelling of Ψ vs. t(h) for direct solar drying of *Amelie* and *Brooks* mangoes slices

Models no.	Parameters				R^2	RMSE	E(%)	χ^2
				Amelie				
1	k=0.07426				0.9069	0.0813	45.0849	0.0128
2	a=0.8534	b=0.0564			0.9372	0.0667	30.1908	0.0090
3	k=0.1824	y=0.6565			0.9804	0.0373	12.3982	7.2331x10^{-4}
4	k=0.07484	y=0.6565			0.9804	0.0373	12.3934	6.9449x10^{-4}
5	a=0.8533	k=0.1036	c=0.1091		0.9716	0.0449	21.1143	5.7077x10^{-7}
6	a=0.6077	k_0=0.2157	b=0.4329	k_1=0.0287	0.9890	0.0286	11.1676	7.8518x10^{-4}
7	a=0.229	k_0=0.2425			0.9541	0.0571	30.9940	0.0043
8	a=0.597	k=0.1881	g=0.02716		**0.9899**	**0.0276**	**11.0031**	**7.6351x10^{-4}**
9	a=0.597	b=0.1444	k_0=0.1881		**0.9899**	**0.0276**	**11.0026**	**7.6557x10^{-4}**
10	a=-0.03809	b=3.541x10^{-4}			0.7062	0.1443	57.3925	0.1032
				Brooks				
1	k=0.05854				0.6807	0.1278	45.3238	0.0134
2	a=0.7526	b=0.03521			0.8344	0.0921	24.4089	0.0077
3	k=0.3248	y=0.4187			0.9479	0.0516	8.6308	0.0077
4	k=0.06817	y=0.4187			0.9479	0.0516	8.6304	0.0077
5	a=0.7724	k=0.1388	c=0.2056		0.9757	0.0353	10.6965	1.9946x10^{-8}
6	a=0.6596	k_0=0.2073	b=0.3556	k_1=0.01162	0.9903	0.0219	6.9971	3.2492x10^{-6}
7	a=0.2094	k_0=0.2131			0.8009	0.1009	34.6598	0.0052
8	a=0.6492	k=0.1995	g=0.01135		**0.9911**	**0.0213**	**6.9610**	**2.9730x10^{-5}**
9	a=0.6492	b=0.05686	k_0=0.1995		**0.9911**	**0.0213**	**6.9629**	**2.7141x10^{-5}**
10	a=-0.03587	b= 0.0003434			0.5338	0.1545	37.2792	0.1249

4.3.4 Influence on product effective water diffusivity

The plots of ln(Ψ) versus drying time *t* for each variety and each drying method were presented in Figure 11. These curves showed an almost linear profile for each drying day (Figure 11). Effective water diffusivities per drying day were thus calculated from the slopes of these lines. Diffusivities were evaluated for three successive drying days and presented on Table 5. Estimated diffusivities ranged between 5x10^{-11} and 1.9x10^{-10} *m²/s* in direct solar drying and between 1.5x10^{-10} and 3x10^{-10} *m²/s* in indirect solar drying. Direct and indirect solar drying diffusivities thus evaluated were close to the range of diffusivity 2.61 x10^{-10} - 1.09 x10^{-9} *m²/s* reported by Dissa and al. (2008) during convective drying of mango from 40 to 60℃. They were also in t he range of foodstuffs diffusivities 10^{-11}-10^{-9} *m²/s* given by Madamba and al. (1996) and in that of many fruits and vegetables such as: Litchi fruit (*0.01322 x10^{-10}-9.629 x10^{-10} m²/s*) (Janjai et al., 2010), pumpkin slices (*3.88 x10^{-10} - 9.38 x10^{-10} m²/s*) (Doymaz, 2007), okra (*4.27 x10^{-10} -13.0 x10^{-10} m²/s*) (Doymaz, 2005). It is obvious that diffusivities identified in direct solar drying were widely lower than those identified in indirect solar drying. For both drying methods, variety did not have enough influence on diffusivity value (Table 5). Moreover, we notice that diffusivity value decreased with the number of drying days in direct solar drying and increased with it in indirect solar drying. This trend is related to the fact that in indirect solar drying the drying temperature increases overall with the number of drying day. So, the diffusivity also increases logically with the temperature as shown by correlation between drying temperature and mango diffusivity established by Dissa et al. (2008).

Table 5: Influence of the type of drying on water effective diffusivity of *Amelie* and *Brooks* mangoes

Variety	1st day		2nd day		3rd day	
	D_{eff}	R^2	D_{eff}	R^2	D_{eff}	R^2
			Direct solar drying			
Amelie	$1.8489x10^{-10}$	0.9883	$1.7080x10^{-10}$	0.9819	$9.5402x10^{-11}$	0.9708
Brooks	$1.7670x10^{-10}$	0.9773	$9.7979x10^{-11}$	0.9844	$5.0343x10^{-11}$	0.9669
			Indirect solar drying			
Amelie	$1.5342x10^{-10}$	0.9898	$1.7976x10^{-10}$	0.9657	$1.9607x10^{-10}$	0.9946
Brooks	$1.6640x10^{-10}$	0.9996	$1.8199 x10^{-10}$	0.9943	$2.0793x10^{-10}$	0.9493

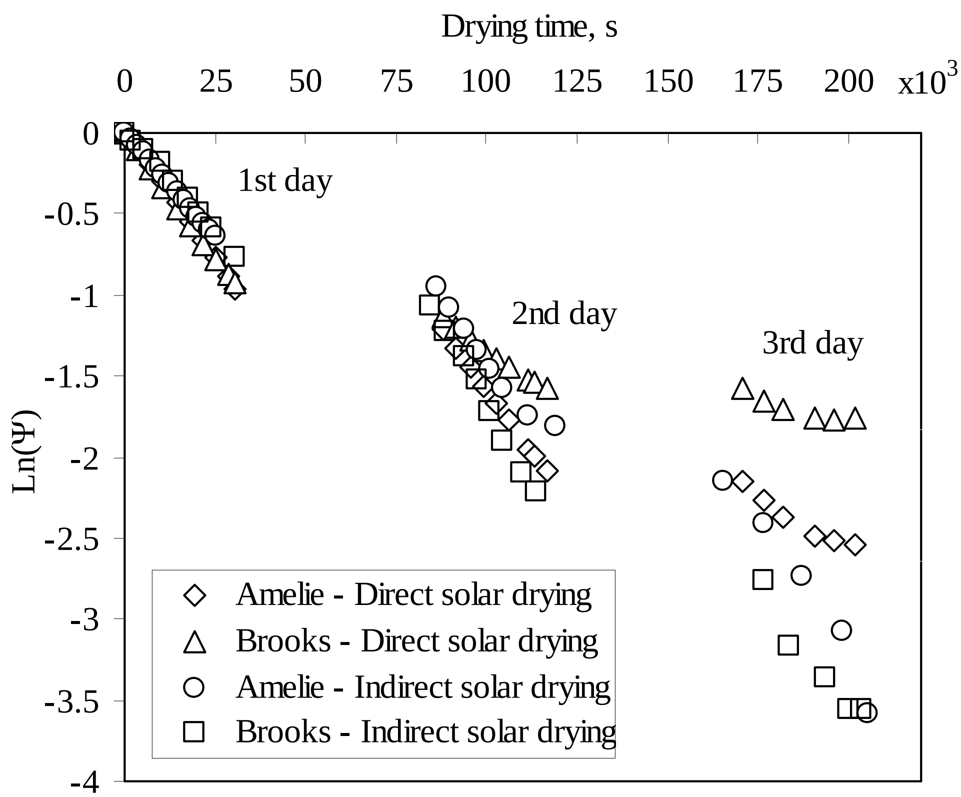


Figure 11. Ln(ψ) versus time(s) of direct and indirect solar drying of *Amelie* and *Brooks* mango varieties

4.3.5. Influence on product drying efficiency and dry product quality

⇒ *Drying efficiency*

Direct and indirect solar drying efficiencies curves for both mango varieties were presented in Figure 12. This figure shows that drying efficiency of the two mango varieties were very close for both drying methods. From the sunrise to the sunset, the direct solar drying efficiency varied overall from 34 to 0.85 % at the 1st day, 7 to 0.53 % at the 2nd day, 4 to 0.0 % to the 3rd day and 0.85 to 0.0 % to the 4th day; while that of indirect solar drying varied from 31 to 44 % at the 1st day, 11 to 48 % at the 2nd day and 2 to 13 % at the 3rd day. For the whole period of solar drying process, direct solar drying efficiency was in the range 0-34 % whereas that of indirect solar drying was in the range 2-48 %. These results confirm that indirect solar drying of mango is much more effective than direct solar drying. This tendency is related to differences in heat and mass transfer mechanisms occurring during these drying methods. Indirect solar dryer is more powerful because it operates by convective heat transfers at temperatures of 20 to 30℃ above the ambient temperature; while t he direct solar dryer operates by radiative heat transfers at ambient temperature. The ranges of our direct and indirect solar drying efficiencies were close to 2.5-47.5 % (with air velocities ranging from 1 to 2 m/s), that reported by Boughali and al. (2009) for an indirect active hybrid solar – Electrical dryer designed for crop drying in the eastern Algerian Septentrional Sahara.

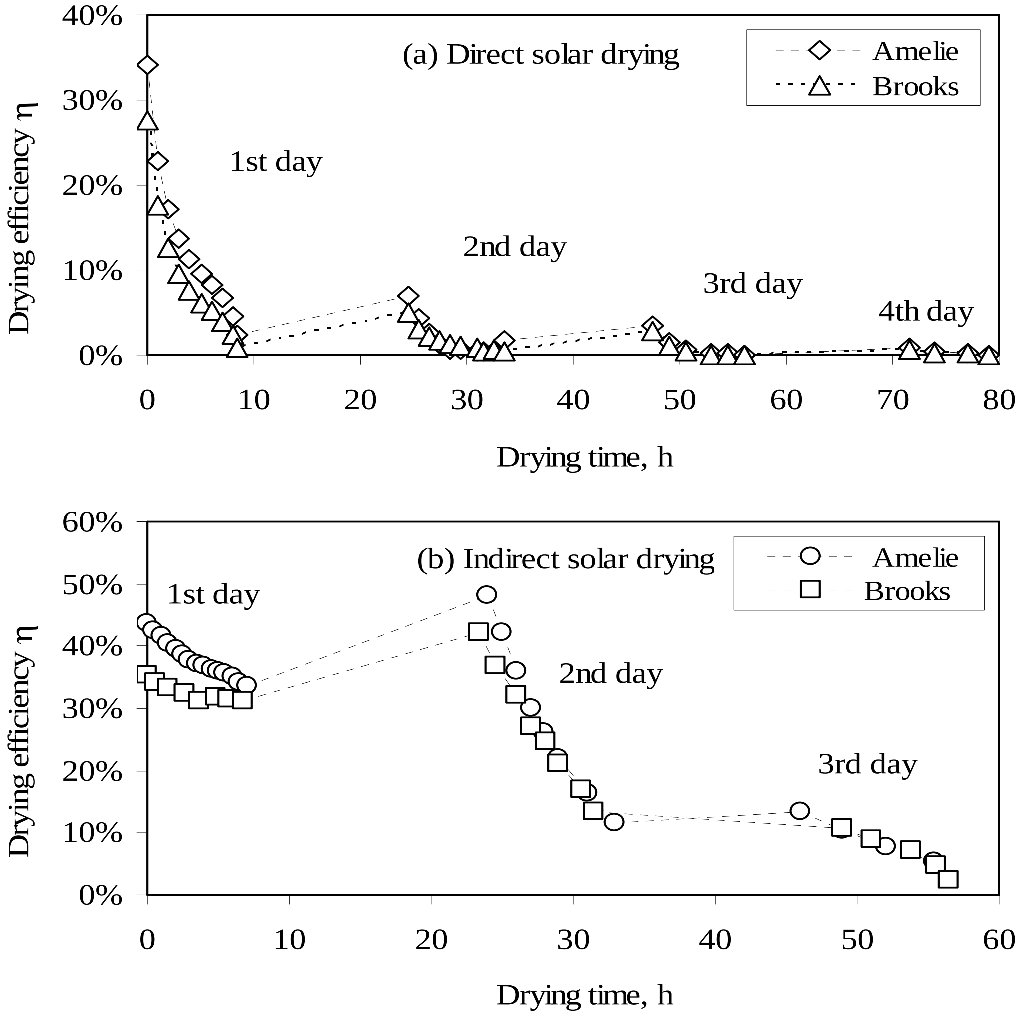


Figure 12. Comparison of direct and indirect solar drying efficiency of *Amelie* and *Brooks* mangoes for three successive drying days

⇒ *Water activity and colour of dry product*

For each method, photo of dry mango slice was illustrated on Figure 13. Also, water activity of dry product was presented on Table 6 and statistical analysis of colour measurements on Table 7. Water activity of dry slices was about 0.62 and 0.73 (respectively for *Amelie* and *Brooks*) in direct solar drying and 0.57 (for both varieties) in indirect solar drying. We noticed that only indirect solar drying allowed reaching water activities lower than 0.6 the reference water activity for biochemical stability of dry fruits reported by several works in the literature (Pott et al., 2005). Indeed, according to Van den Berg & Bruin (1981), for $A_w \leq 0.6$, biological products are suitably preserved because micro-organisms cannot any more extract water for their development and enzymes become inactive. According to Table 7, the average redness of fresh slices, direct solar dried slices and indirect solar dried slices were respectively 50, 52 and 53. Thus, there was no significant difference between redness of dry slices and that of fresh slices. Likewise, taking into account the standard deviation of measurements, we can consider that there was no significant difference between colour of direct solar dried and indirect solar dried slice and that of fresh slices (6 for indirect solar drying and 5 for direct solar drying). We can deduce that direct or indirect solar drying does not affect significantly colour of mango slices. Thus, each of these drying methods allows keeping most apparent quality of mango.

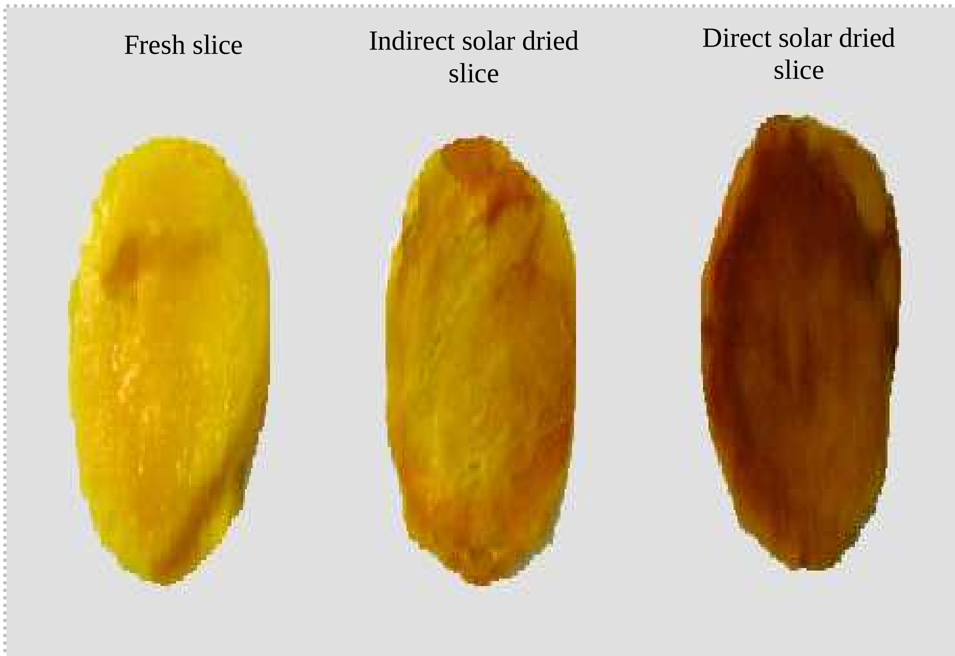


Figure 13. Illustration photo of colour change after direct and indirect solar drying of *Amelie* mango

Table 6: Critical water content, final moisture content and dry product water activity of *Amelie* and *Brooks* mangoes by direct and indirect solar drying

Variety	X_0(d.b)	m_s(g)	X_{cr}	Ψ_f	X_f(d.b)	Aw_f
				Direct solar drying		
Amelie	6.01	35.79	4.808	0.0583	0.3503	0.6567
Brooks	5.83	26.59	4.664	0.1615	0.9431	0.7735
				Indirect solar drying		
Amelie	6.01	451.63	4.207	0.0278	0.1668	0.6246
Brooks	5.83	369.64	4.3725	0.0285	0.1660	0.6234

4.4 Comparison of performances, usefulness and manufacturing cost of dryers

The characteristics of both types of dryer and their manufacturing cost were presented on Table 2. Each dryer was mainly made with local materials available in local markets of West African cities. In addition to local materials, the indirect solar dryer required additional elements such as extractor, glass and porous absorber. Because of these additional elements, the indirect solar dryer cost 3 to 4 times more expensive than direct solar dryer. Moreover, the indirect solar dryer had a more complex configuration and would be more difficult to realize by the local craftsmen. So, it would require a preliminary training for these craftsmen. The direct solar dryer is easy to realize but has a configuration that does not allow a fast drying of the product. It would be suitable for a traditional drying on a family scale and inappropriate for a great production of dry mango on an industrial or a semi-industrial scale. Indeed, this solar dryer without solar energy collector system presents enormous deficiencies with respect to requirements related to product biochemical stability: heterogeneity of drying, incomplete drying in wet period, stop of drying after the beginning of the rain during the raining season, often poor quality of drying. By considering the whole of drying parameters, we can conclude that indirect solar drying offered more satisfaction both in drying duration and final water content. In conclusion, the direct solar dryers are less expensive than the indirect solar dryers, but present longest drying time and sometimes dry product of quality much lower than that of indirect solar dryers. Thus, the usefulness of direct solar dryers should be limited to traditional drying on a family scale whereas the indirect solar dryer would be appropriate to an industrial or semi industrial scale for regional consumption or for dry product exports.

Table 7. Colour parameters of fresh, direct and indirect solar dried *Amelie* mango samples

Sample	Replicates	CIE LAB colour parameters			Colour difference	
		L	a	b	ΔE_0 [(a)]	ΔE [(b)]
	White standard	**97.94**	**-0.055**	**1.805**		
Fresh slice	1	59.85	52.05	42.25	76.1681	
	2	60.25	52.5	42.25	76.2782	
	3	63.3	53.45	44.3	76.6064	
	4	63	50.6	41.65	73.3100	
	5	61.85	52.5	43.35	76.0954	
	Mean value	**61.65**	**52.22**	**42.76**	**75.6766**	
	Standard deviation	**1.5640**	**1.0396**	**1.0574**	**1.3456**	
Direct solar dried slice	1	67	51.4	39.55	70.9196	6.2928
	2	70.1	51.7	39.55	69.8450	9.0541
	3	67.65	51.6	40.1	71.0790	6.5924
	4	63.9	50.25	37.9	70.6552	5.7064
	5	61.7	47	36.2	68.6333	8.3836
	Mean value	**66.07**	**50.39**	**38.66**	**70.1333**	**6.3004**
	Standard deviation	**3.2942**	**1.9819**	**1.6037**	**1.0093**	**1.4371**
Indirect solar dried slice	1	63.8	51.2	38.1	71.4839	5.2324
	2	62.3	51	36.8	71.4246	6.1182
	3	60.2	55.5	35.7	75.2299	7.9186
	4	63.4	55.1	37.9	74.4173	5.9141
	5	66.7	50.8	40.3	71.0214	5.7940
	Mean value	**63.28**	**52.72**	**37.76**	**72.6586**	**5.2827**
	Standard deviation	**2.3679**	**2.3637**	**1.7141**	**1.9540**	**1.0177**

[(a)] Difference with the standard white colour
[(b)] Difference with the colour of fresh slice

5. Conclusion

In this work, a comparative study was carried out between direct and indirect solar dryings of two main West African mango varieties (*Amelie* and *Brooks*). Direct and indirect solar drying curves were experimentally established and modeled. Influence of drying method on drying characteristics such as drying kinetics, drying rates, effective diffusivity and drying efficiency was analyzed for the whole drying days and the quality of dry slices was evaluated. The results showed that:

1) In indirect solar drying, the tray position in the dryer and the type of variety did not have enough influence on drying curves whereas in direct solar drying these influences were very significant.
2) Indirect solar drying kinetics were best fitted by "Approximations of diffusion model" (with $R^2 \approx 0.99$, RMSE≈0.0387, E<12% and $\chi^2 < 10^{-5}$) while those of direct solar drying were best fitted by both "Verma et al." and "Approximation of diffusion" models (with $R^2 \approx 0.99$, RMSE<0.0276, E<12% and $\chi^2 < 10^{-3}$).
3) In indirect solar drying, the final water contents obtained for both mango variety were in the range of preservation water contents given by the literature, whereas in direct solar drying only *Amelie* variety gave a satisfactory final water content.
4) For both varieties, indirect solar drying rates and water diffusivities were the highest; and diffusivities increased with the number of drying days between 1.5 $\times 10^{-10}$ and 2 $\times 10^{-10}$ m²/s whereas in direct solar drying their values decreased with the number of drying day between 5 $\times 10^{-11}$ and 1.85 $\times 10^{-10}$ m²/s.
5) Indirect solar drying with an average final water content of 16.6 % db corresponding to dry product water activity of 0.57 for both varieties was more efficient than direct solar drying with final water contents of 24.83 % db for *Amelie* and 66.31 % db for *Brooks* corresponding respectively to dry product water activities of 0.62 and 0.73.
6) With efficiency from 2 to 48 % the indirect solar dryer was found to be much more effective than direct solar dryer with efficiency from 0 to 34 %.
7) Both drying methods lead to good apparent quality of dry slices.

Thus, the indirect solar dryer was found to be the most efficient, but also the most expensive and was suitable for industrial or semi industrial mango drying, whereas the direct solar dryer was appropriate to a family scale traditional mango drying.

Appendix

The global solar radiation of the site (in *W/m²*) was given by the following formula :

$$G = G_D + G_d$$

(A.1)

where: G_D and G_d are respectively the direct and the diffuse radiations given by (Daguenet, 1985):

$$G_D = G_o CA \exp\left(\frac{-BP}{1000 \sinh}\right) \times \cos i$$

(A.2)

$$G_d = \frac{1}{2}\left[G_{dh}(1+\cos\beta) + A_0(G_{Dh} + G_{dh})(1-\cos\beta)\right]$$

(A.3)

where G_0 is the solar constant (G_o=1353 W/m²), C the solar radiation correction factor due to earth-sun distance variation (*W/m²), G_{Dh}* and G_{dh} the direct and diffuse radiations on a horizontal plane, P the atmospheric pressure, i the angle between solar rays and the normal direction of the collecting surface (*deg*), h the sun altitude expressed in degrees (*deg*), A_0 the albedo, A and B the characteristic coefficients of the sky state and β the tilt angle of the collecting surface (*deg*).

where: $C \approx 1 + 0.034 \cos[30(n_0 - 1) + n_1]$,

$$\cos i = \sin\beta \cos h \cos(\alpha - \upsilon) + \cos\beta \sin h,$$

$$G_{Dh} = G_o CA \exp\left(\frac{-BP}{1000 \sinh}\right),$$

$$G_{dh} = G_o C\left[0.271 - 0.2939 A \exp\left(\frac{-BP}{1000 \sinh}\right)\right] \times \sinh$$

, $\sin h = \sin\phi \sin\delta + \cos\delta \cos\phi \cos\omega_s$

where: n_0 is the number of the month in the year, n_1 the number of the day in the month, α the solar azimuth angle (*deg*), β the tilt angle of collector surface (*deg*), υ the angle between the local meridian and the normal of the collector surface (*deg*), ϕ the latitude, ω_s the sunrise hour angle (*deg*) and δ the solar declination angle (*deg*).

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