Drying Performance, Quality Characteristics, and Financial Evaluation of Indian Mackerel (Rastrilliger Kangurta) Dried by a Solar Tunnel Dryer

B. R. Chavan[1*], A. Yakupitiyage[2], and S. Kumar[2]
[1*] College of Fisheries (Dr. BSKKV), Ratnagiri, (MS), India
[2]School of Environment, Resources and Development, Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathum Thani 12120, Thailand
[*] Corresponding author. Tel: + (91-2352) 232241, Fax: + (91-2352) 232241
Email: brc15672@yahoo.co.in (B. Chavan)

Abstract

Eight drying trials were conducted in each solar tunnel dryer (STD) and compared with open sun drying (OSD). The drying behavior of mackerel drying in STD was studied by comparing eleven different drying models. The *Midilli* model provided the highest R^2 (0.9928), lowest χ^2 (0.000406) and RMSE (0.0164). The drying time required for STD and OSD were 27 and 48 h, respectively. The overall drying efficiency of the STD and OSD was about 19.87 and 12%, respectively. STD significantly influenced the biochemical properties such as Free fatty acid (FFA), Peroxide value (PV), Thiobarbituric acid (TBA), total volatile bases nitrogen (TVB-N), Trimethylamine nitrogen (TMA-N) and histamine of dried mackerel. There was a significant positive relationship between drying temperature and time (R^2>0.85). No microbial growth on dried product was found in STD dried fish. Sensory quality of dried mackerel was judged by ten experienced sensory panel experts using a seven point hedonic scale. The fish dried at temperatures ranging from 40-46 ^oC for 20-30 h were awarded the highest scores by the sensory panel. Contour plots of dried mackerel showed that for all sensory attributes examined, panelists preferred fish dried with STD. Time series sensory evaluation of the shelf-life revealed that dried mackerel stored at ambient temperature is acceptable to the sensory panel until 154 and <98 days, for STD and OSD, respectively. The financial analysis showed that the average net income $year^{-1}$ (for 10 years) is about 45,223 Indian Rupees (INR) and the pay-back period is <1.5 years.

Key words: Solar tunnel dryer, dried mackerel, mackerel quality, mackerel drying modeling; open sun drying

1. Introduction

Usually, fish drying is done by laying the fishes on open beaches, roadsides, mats or even on the ground in open sun during the non-monsoon period. There are several disadvantages encountered during this drying process, including contamination by dust, sand and stones, slow drying, blowfly infestation, attacks by rodents, ants, insects, chickens, dogs, etc. All these factors have led to low quality dried fishes and are unhygienic for human consumption. Most low cost technologies such as sun-drying are time consuming. One of the best ways of improving this problem is to enhance the quality by improved processing techniques, so that they are accepted by high income groups. This will also considerably enhance the income of fishermen [1].

The research performed so far on solar drying at various institutes has concluded that to meet the increasing demand for food preservation in developing countries, simple, cheap but efficient solar dryers, supplied with a fan for ventilation and supplementary heat sources, should be developed [2]. Several designs of solar dryers have been recently proposed for drying applications of fish in developing countries and still a good deal of work is continuing in this direction [3]. The Asian Institute of Technology (AIT) has developed packages on solar box dryer and solar-biomass hybrid dryers [4].

Solar tunnel dryers have been tested with agricultural products such as bananas, chilis and radishes, and the performance is found to be good as they considerably reduce the fluctuations in the drying air temperature with fluctuating solar radiation [4]. Mathematical modeling has been widely used for the analysis of drying processes. There is limited information available on the drying kinetics of fish and prawn [5]. However no studies have been found on the drying kinetics of mackerel (Rastrilliger kangurta) in solar tunnel dryer. A study was conducted to develop the mathematical model for the drying of mackerel and also to study the drying performance, quality characteristics, and financial evaluation of Indian Mackerel (R. kangurta) dried by a solar tunnel dryer. Mackerel (R. kangurta), is a pelagic shoaling low value fish.

2. Materials and Method

2.1 Fish

Fresh mackerel (R. kangurta) were purchased from Mahachai fish landing centre, Thailand. Fish were then transferred to the laboratory in polystyrene boxes with crushed ice within 2 h of purchase. The mean weight and length of fish were 78.22±1.19 g and 18.27±0.80 cm, respectively. The fishes were washed with potable water and packed in 200 gauge high-density polythene sacks and stored at -20oC until use.

2.2 Preparation for salting

Fresh mackerels were dressed by removal of fins, scales, and viscera and were split open in a butterfly style by cutting along the backbone from head to tail. The guts and gills were removed and a cut was made under the backbone to open out the thick part of the flesh and expose the greater surface area for salt-drying. Dressed fishes were soaked in separate containers containing 25% (w/v) brine solution of NaCl for 4 h [6]. A fish-to-brine ratio of 1:4 L was used. Following brining, fishes were placed skin side down in aluminum trays and slightly washed with tap water and drained and loaded in an experimental dryer.

2.3 Solar tunnel dryer

The AIT solar tunnel dryer has a width of 1.8 m and a total length of 8.25 m. The first 4 meters serve as a solar air heater, and the remaining 4.25 meters constitutes the drying tunnel. The side height for the air flow is 0.07 m to accommodate the trays with the products. In order to have flow rate variation from about 300-600 m^3/h, the air flow rates were controlled by using five AC-driven fans of 14 W capacities, that are placed in front of the collector. However, for the actual drying experiment only three AC-driven fans were used to maintain the required temperature in the drying chamber.

Glass wool insulation with thickness of 4 cm is used to reduce the heat losses.

A 0.2 mm thick UV stabilized polyethylene sheet is used as a glazing material for the dryer. The transmissivity of the plastic cover is about 0.89 for beam radiation. The covering sheet is tilted like a roof to prevent water entering or even flooding during rainfall. The roof supports by the side frames and metal string running from the collector inlet to the dryer outlet are connected so that the covered plastic does not sag. The plastic cover consists of two pieces, one each for the collector and the dryer. The part of the collector is fixed at all four edges. For spreading out the drying material inside the tunnel dryer, the cover foil has to be removed. This can be done easily by rolling up the foil on a crank made of galvanized pipe that is riveted to one end of the dryer cover. At the end of the dryer, an aluminum mesh prevents any insects from entering the dryer. The support for the collector dryer unit is made of small brick pillars. Ten pillars, each of 0.3*0.3 m^2 are piled to a depth of 0.2 m below the surface. The height of the brick work is 0.8 m above the ground (Fig.1) [7]

2.4 Experimental Design

Eight drying trials were carried out by placing the dressed and salted fish in STD and open sun with three replicates for evaluating the effect on quality characteristics of mackerel.

2.5 Experimental Methodology

Dressed and salted mackerel (25 kg) were dried in STD from 08:00 to 17:00. The fishes were dried using the rise of internal temperature by solar collector until evening and were removed at early evening. At night, the fishes were piled in plastic bins which were kept inside until the next morning and then continue to dry in the STD. Simultaneously processed fishes were dried in open sun. The dressed and salted fishes were

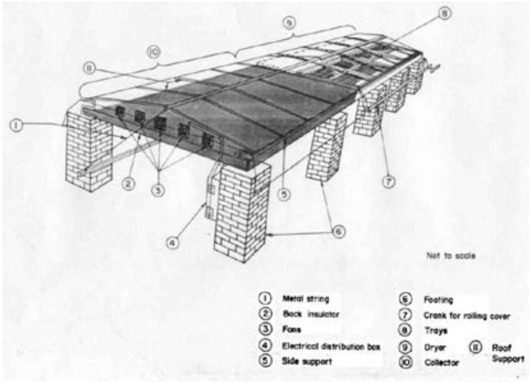

Figure 1 Solar Tunnel Dryer

placed on the aluminum mesh tray in open sun from 8:00 until 17:00. At night, fishes were piled in plastic bins which were kept inside until the next morning and then, continued to dry in the open sun. The fish were dried until the final moisture content reached <17% (w.b.).

2.6 Dryer operating procedure

Openings of the dryer were closed in the early mornings in order to raise internal temperature as quickly as possible. Temperatures measurements and recordings were made by air probe sensors K-type thermocouples connected to a data logger (Campbell CR10KD). Thermocouples were calibrated before fixing them in the experimental dryer. Dry and wet bulb temperatures in the drying area and outside the dryer were measured at hourly intervals. Relative humidity of the tunnel dryer was determined by using a psychometric chart. The air flow rate was measured with hot wire anemometer at the outlet of the drying chamber. The solar radiation and other meteorological data were obtained from the meteorological station at AIT. A top-loading balance with 50 kg capacity was used to measure the weight of fresh and dry fish. The fish were dried until a final moisture content was reached (<17% (w.b.)).

2.7 Drying Efficiency

Drying efficiency of the STD has been estimated by taking solar energy input to the collector and dryer parts into account. Drying efficiency of mackerel was estimated by considering: total radiation incident and initial and final weight of the product and thus the amount of water evaporated. The system drying efficiency is defined as the energy used to evaporate the moisture in the product divided by the energy input to the dryer [8]. System efficiency for natural convection of solar dryer is given by:

$$\eta_s = \frac{WL}{IA} \quad (1)$$

Where, η_s = Drying efficiency of system

I = Hourly average solar radiation on the aperture surface (kWh)

A = Aperture area of the dryer (m^2)

W = Weight of water evaporated from the product

L = Latent heat of evaporation of water

2.8 Drying Model for Mackerel Drying in Solar Dryer

The published literature revealed that there is no single drying model which is suitable for describing the drying kinetics of all products. However, the mathematical models listed in Table 1 were found to describe the thin layer drying of agricultural products [9]. Therefore, the mathematical models were used for predicting the drying curves [10] of mackerel in STD and OSD methods.

2.9 Physicochemical, Biochemical and microbiological analysis

The water activity (a_w) was measured by using a tripette and renaud agro CX-2, France. Free fatty acid (FFA), Thiobarbituric acid (TBA) value, Peroxide value (PV), changes in biogenic amines such as total volatile bases nitrogen (TVB-N), trimethylamine (TMA-N), and histamine were analyzed by using standard methods [21]. Total plate counts were determined by using plate count agar (PCA) (Hi media, Bombay) incubated at 37 °C for 24 hours; Coliforms on Mac-Conkey Agar (Merck Darmstadt, Germany), incubated at 37 °C for 24 h; moulds by using potato dextrose agar (PDA), incubated at 30 °C for 48 h; staphylococci by using baird-parker agar (BioMerieux, Etoile, France), incubated at 37 °C for 48 h. For halophilic bacterial counts, decimal serial dilutions were prepared with homogenizing solution including 15% NaCl. They were plated on to standard PCA containing 15% NaCl in duplicate and incubated at 37 °C for 48 h [22].

Table 1 Mathematical models evaluated for the drying curves

No	Model name	Model equation	Products	Ref.
1	Newton	MR=exp(-kt)	Apple slices	[11]
2	Page	$MR=exp(-kt^2)$	Bananas	[12]
3	Henderson and Pabis	MR=a.exp(-kt)	Shrimp and fish cake	[13]
4	Logarithmic	MR=a.exp(-kt)+c	Prawn and Chelwa fish	[5]
5	Two term	$MR=aexp(-k_0t)+bexp(-k_1t)$	Rice	[14]
6	Two-term exponential	MR=aexp(-kt)+(1-a) exp(-kat)	Corn ears	[15]
7	Wang and Singh	$MR=1+at+bt^2$	Rough rice, lemon grass	[16]
8	Diffusion approach	MR=aexp(-kt)+(1-a)exp(-kbt)	Sultana grape	[17]
9	Verma *et* al.	MR=aexp(-kt)+(1-a)exp(-gt)	Rice	[18]
10	Modified Henderson and Pabis	MR=aexp(-kt)+bexp(-gt)+cexp(-ht)	Fresh and semi dried Fruits	[19]
11	Midilli model	$MR=aexp(-kt^n)+bt$	Red chili, Pistachio	[20]

2.10 Sensory Evaluation

For sensory evaluation, dried mackerel were immersed in potable water for 30 minutes to
remove salt and steamed for 15 minutes. Ten experienced assessors judged the acceptability of cooked samples using a seven point hedonic scale. The quality scoring system used was modified from [23, 24]. The scale points were: Like extremely=7-6, Like very much=6-5, Like slightly=5-4, neither like nor dislike=4-3, Dislike slightly=3-2, Dislike very much=2-1, Dislike extremely=1. The shelf life of products was assessed from the regression line of the mean overall acceptability scores for the storage period. A quality score of 3 was considered as the limit of acceptability. Sensory assessmentincludes the taste, texture, odor, appearance, and overall acceptability [25].

2.11 Statistical analysis

The coefficient of determination (R^2), reduced chi-square (χ^2) and the percentage of root mean square error (*RMSE*) were used for selecting the best fit equation to describe the drying process. All data are expressed as mean and S.D. Statistical analyses were performed by non-linear regression. In all cases *P* (0.05 was taken as the significance level). These parameters can be calculated from:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{2}$$

Where, χ^2 = Chi-square
MR_{exp} = experimental moisture ratio
MR_{pre} = predicted moisture ratio
N = number of observations
N = number of constant

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \tag{3}$$

$$MR = \frac{W_t - W_e}{W_i - W_e} \tag{4}$$

Where, Wt = Moisture content at time t (d.b.)
Wi = Moisture content at time= 0(d.b.)
We = Moisture content in equilibrium state

3. Results and Discussion

3.1 Characteristics of drying conditions

During a drying experiment at daytimes, the collector is heated by the solar radiation and reaches higher temperatures in the collector and drying chamber. The drying chamber reaches the highest temperatures; this could be due to direct and indirect heating. The direct heating is caused by the solar radiation that shines directly inside the drying chamber and on the fish. The indirect heating is caused by the collector’s heated air, which is blown into the drying chamber. During experimentation, the temperature profile does not show constant temperature (Fig. 2). This can be due to the fact that the tunnel dryer temperature is based on the solar radiation, which was not constant. The relative humidity of drying air is a critical factor controlling the drying rate of the product. The lower the relative humidity, the greater is the absorbing capacity of drying air. The relative humidity of air at the outlet of the dryer showed that the air still has a considerable drying potential, implying that the rated capacity of the dryer has not been fully utilized.

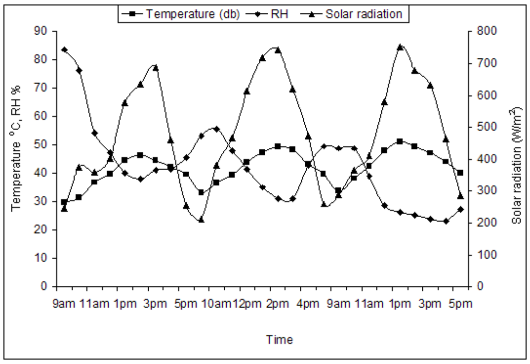

Figure 2 Variation of temperature, relative humidity and solar radiation during mackerel drying in STD

The solar radiation also varied day to day and ranged from 213-752, and 219-761W/m^2 for STD and OSD during the drying process, respectively. The air flow rate was not constant. During a high insolation period, more energy was received by the collector, which was intended to increase the drying air temperature, but it was compensated by an increase of air flow rate. During low solar insolation period less energy was received by the collector and air flow rate was low. Hence, the decrease in temperature due to low solar insolation was compensated by the increase in temperature due to low air flow rate. This resulted in minimum variation of the drying air temperature throughout the drying period and saved the dried fish from partial cooking due to excess temperature. The same result was found during the drying of silver jew fish in STD [26].

3.2 Drying and drying rate curves

The moisture content of processed fish was 71.60% which reached 16.09% within 27 h of drying time in the STD drying method. While OSD took 44 h of drying to bring down the moisture content of a similar sample of mackerel to 16.22% (Fig 3)

This could be due to the fact that the fish in the experimental dryer received energy both from the collector and from incident solar radiation, while open sun dried samples received energy only from incident radiation and lost a. significant amount of energy to the environment.

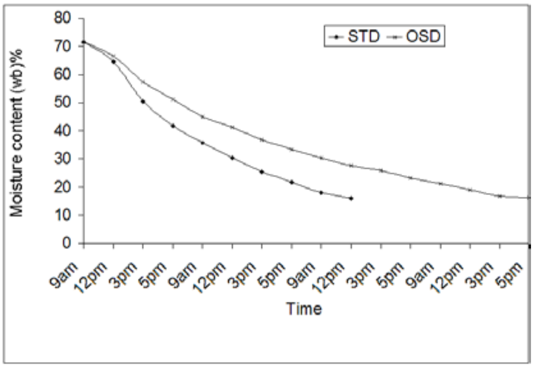

Figure 3 Drying curves of mackerel in STD and OSD

During drying, the salted fish showed greater moisture loss at the initial stage of drying than during the following stage. This can also be seen from the drying rate of the fish, where a higher drying rate was observed at the initial drying stage, which implies that a greater amount of moisture was removed during that stage (Fig. 4). This was caused by higher moisture content and lower salt content in fish, thus allowing the faster moisture removal at the initial stage of drying.

Figure 4 shows that the mackerel did not show any constant drying rate period, and had a falling rate period. The drying rate decreased as the drying proceeded, entering the subsequent falling rate period. It was also found that the drying rate in the experimental dryer was higher during the first 6 h and then slowed. The drying rate for mackerel showed fluctuations and this could be because the samples were taken out of the experimental tunnel dryer for measurement more often. In STD, drying of mackerel is fast, as compared to the open sun drying method, because the drying air temperature was higher than the open sun drying method.

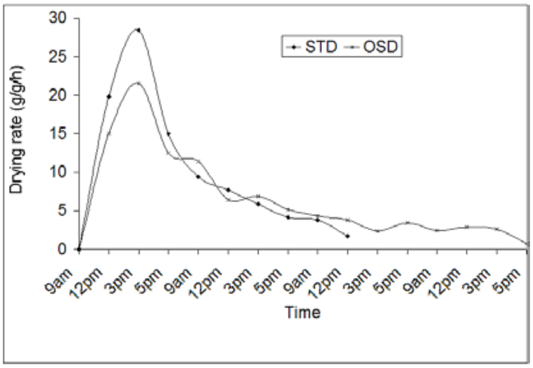

Figure 4 Drying rate curves of mackerel in STD and OSD

3.3 Drying efficiency

The overall drying efficiency of the STD is estimated to be about 19.87% during mackerel drying. The first day of mackerel drying had higher efficiency and it reduced during the following days. This was mainly because at the initial stage of drying, mackerel had higher moisture content and a higher amount of water was evaporated. The drying efficiencies of STD were 50.5, 17.6 and 3.2% during the first, second and third days, respectively. The overall drying efficiency of open sun drying was 12%. During the drying process drying efficiencies were 38.55, 10.87, 5.29, 2.64 and 2.32% during first, second, third, fourth and fifth days, respectively (Table 2).

3.4 Evaluation of drying models

The drying curves obtained from experimental drying method were fitted with moisture ratio equations (Table 1). However, the moisture ratio (*MR*) was simplified to M/M_0 instead of $(M-M_e)/(M_0-M_e)$ because relative humidity of the drying air sometimes fluctuated to a low level in the drying chamber [27]. The best drying model was selected based on the maximum coefficient of determination (R^2), minimum values of reduced chi-square (χ^2), and the percentage of root mean square error (*RMSE*) [17]. Table 3 shows the results of statistical analysis undertaken in each model for STD and OSD methods. The models were tested and it is observed that the *Midilli* model recorded the highest R^2 (0.9928) with lowest χ^2 (0.000406) and *RMSE* (0.0164), in STD. The *two term* model recorded the highest R^2 (0.9997) with lowest χ^2 (0.000431) and *RMSE* (0.0119) in open sun drying of mackerel.

Table 2 Drying efficiency of solar tunnel dryer and open sun drying

Parameters	Solar tunnel drying				Open sun drying					
	Drying period (days)			Overall	Drying period (days)					Overall
	1	2	3		1	2	3	4	5	
Initial weight of Mackerel (kg)	25.0	14.6	9.6	25.0	25	14.6	11.3	9.8	9	25
Final weight of Mackerel (kg)	12.2	9.6	8.7	8.7	14.6	11.3	9.8	9.0	8.5	8.5
Initial Moisture content (% wb)	71.6	41.8	25.5	71.6	71.58	51.29	36.9	27.65	21.3	71.58
Final Moisture content (% wb)	41.8	25.5	16.1	16.1	51.29	36.85	27.7	21.32	16.2	16.22
Water evaporated (kg)	12.8	5.0	0.9	16.3	10.40	3.30	1.49	0.79	0.52	16.50
Latent heat of Evaporation(kJ)	2,272	2,272	2,272	2,272	2,272	2,272	2,272	2,272	2,272	2,272
Energy used to evaporate water (kJ)	29,082	11,365	2,047	37,034	23,629	7,498	3,385	1,794	1,181	37,488
Duration of energy supply (min)	540	540	540	1,620	540	540	540	540	480	2,640
Average solar radiation (W/m^2)	444	498	495	479	473	532	494	524	442	493
Collector area (m^2)	4	4	4	4	4	4	4	4	4	4
Energy from solar collector (kJ/m^2)	57,557	64,627	64,195	186379	61,300	68,947	64,022	67,910	50,918	312,364
Total energy supplied to the system (kJ)	57,557	64,628	64,195	186379	61,300	68,947	64,022	67,910	50,918	312,364
Drying Efficiency (%)	50.5	17.6	3.2	19.87	38.55	10.87	5.29	2.64	2.32	12

Hence, the *Midilli* and *two term* models gave better prediction for STD and OSD, respectively, and satisfactorily described drying characteristics of mackerel. The experimental and predicted values by Midilli and two term models of moisture ratio of dried mackerel in STD and OSD methods are shown in Figure 5. It is found that the differences between the experimental and predicted values are very minimal, showing that the models satisfactorily describe the characteristics of the drying process.

4. Quality Characteristics of dried mackerel

4.1 Effect on biochemical properties of mackerel

By drying, STD was significantly influencing (P<0.05) the biochemical properties of dried mackerel. Mackerel dried in STD showed very high corresponding coefficients of determination, where all R^2 were greater than 0.90, except TBA value (Fig. 6).

During 120 days of storage dried mackerel decreased in quality. This was shown by the increase of biochemical contents as the result of decomposition of lipid and nitrogenous substances and the decrease of sensory scores. FFA contents increased gradually throughout the storage period. FFA value and PV increased slowly with storage period, as the fish muscle contains low levels of antioxidants such as ascorbic acid and tocopherols; however, their concentrations declined as storage time increases [28].

There was significant change in TBA values in dried mackerel with storage period at ambient temperature; however these values did not exceed 3.0 mg malonaldehyde kg^{-1} in STD, while in open sun dried fish, TBA values was increased and reached to values of 3.81 mg malonaldehyde kg^{-1}. It has been found that TMA is mainly formed

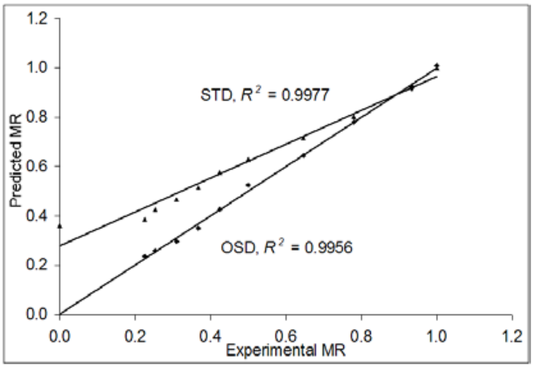

Figure 5 Experimental and predicted MR by *Midilli* model in STD and *two term* model in OSD

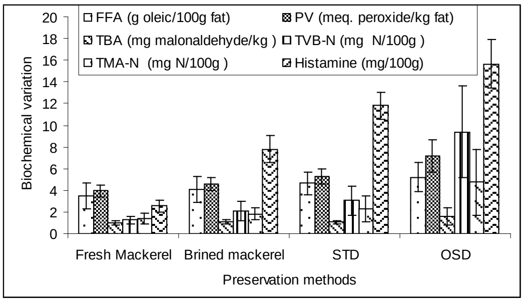

Figure 6 Variations of bio-chemical properties of mackerel

through bacterial decomposition of TMAO. The results tend to confirm the observations as values varied throughout storage and the limit of acceptability, 10-15 mg TMA-N/100 g [29] was never approached. The TVB-N contents increased in dried mackerel throughout the storage period in the STD. Srikar et al. [30] found that the dried fish stored at ambient temperature had higher values of TVB-N than the fish stored at lower temperature

The values of histamine increased slowly in the experimental drying method but within the acceptable limit up to 120 days of storage. In the open sun drying method the histamine level increased significantly from 14.37 mg kg^{-1} at the beginning of storage to reach 52.19 mg kg^{-1} at the end of storage. Increases in histamine contents in dried fish can be from the

Table 3 Values of the drying constants and coefficients of different models determined through non linear regression method in STD and OSD

Model No	R^2	χ^2	*RMSE*	Model constants					
Solar tunnel dryer									
1	0.9605	0.001836	0.0462	k = 0.054					
2	0.9782	0.000889	0.0300	k = 0.0318,	n = 1.1929				
3	0.9553	0.001336	0.0365	a = 1.0518,	k = 0.0577				
4	0.9669	0.001444	0.0348	a = 1.1370,	k = 0.0492	c = 0.0955			
5	0.9553	0.002004	0.0365	a = 0.4912,	k_0= 0.0577,	b = 0.5605,	k_1= 0.0577		
6	0.9219	0.023800	0.0312	a = 1.0000,	k = 0.0511				
7	0.9778	0.001619	0.0363	a = -0.0482,	b = 0.0008				
8	0.9605	0.002571	0.0462	a = 1.0000,	k = 0.0522,	b =1.0000			
9	0.9614	0.014218	0.0169	a = 1.0721,	k = 0.0522,	g = 0.0522			
10	0.8321	0.111391	0.0448	a = 0.8089	k = 0.0543,	b = 0.2029,	g = 0.054,	c = 0.001,	h = -0.4089
11	0.9928	0.000406	0.0164	a = 0.9991,	k = 0.0326,	n = 1.2664,	b = 0.0048		
Open sun drying									
1	0.9996	0.000480	0.0166	k = 0.0352					
2	0.9989	0.000435	0.0145	k = 0.0407,	n = 0.9543				
3	0.9996	0.000554	0.0165	a = 0.9959,	k = 00.035				
4	0.9959	0.000468	0.0123	a = 0.9257,	k = 0.0421,	c = 0.0862			
5	0.9997	0.000431	0.0119	a = 0.3550,	k_0= 0.066,	b = 0.6605,	k_1= 0.0261		
6	0.9996	0.044429	0.0131	a = 0.4556,	k = 0.05400				
7	0.9895	0.000746	0.0191	a = -0.0327,	b = 0.00035				
8	0.9996	0.000673	0.0166	a = 1.0000,	k = 0.0352,	b =1.0000			
9	0.9996	0.000673	0.0166	a = 1.2607,	k = 0.0352,	g = 0.0352			
10	0.9967	0.000863	0.0130	a = 0.6606,	k = 0.0261,	b = 0.1774,	g = 0.0665,	c = 0.1774,	h = 0.06651
11	0.9959	0.000479	0.0125	a = 1.0116,	k = 0.0399,	n = 0.992,	b = 0.00108		

formation of histidine decarboxylase enzyme, which can continuously produce histamine in the fish, even if bacteria are not active [31].

4.2 Effect on microbial growth

On drying in STD, the total bacterial count was "not detected" in the experimental dryer, whereas open sun dried mackerel total plate count decreased and reached a level of 0.12±0.01 cfu g^{-1} for OSD. After the final drying the bacterial load was almost eliminated. With respect to total halophilic amine forming bacteria in the mackerel, the initial counts were lower than 2.8±0.39 cfu g^{-1}, which was increased on the salting stage and eliminated after drying in the experimental dryers (Fig. 7). Also, no histamine forming bacteria were detected in the dried mackerel since most of the bacteria with decarboxylase cannot tolerate high salt concentration and reduced moisture content. In the STD method, microbial growth was not found in the initial storage period. In the open sun dried fish, total plate count and Staphylococci growth was found, but it was <30 cfu g^{-1} at the beginning of storage and increased significantly (p<0.05) at the end of storage period. There was no discoloration of the product during 120 days of storage.

Halophilic count showed an increasing trend after a 90 day storage period for dried mackerel dried with STD method. This is because the water activity of the dried mackerel increased from 0.66 to 0.70 at the end of 90 days storage period, which is more suitable for the growth of halophilic bacteria [32]. The oxidative and hydrolytic rancification (enzymatic reaction) in the dried product helps to increase the water activity from 0.66 to 0.70. The oxidative rancification were because the dried product was kept at room temperature in LDPE bags. The hydrolytic rancification occurred due to the presence of enzymes in the dried fish. The halophilic count was within the acceptable limit.

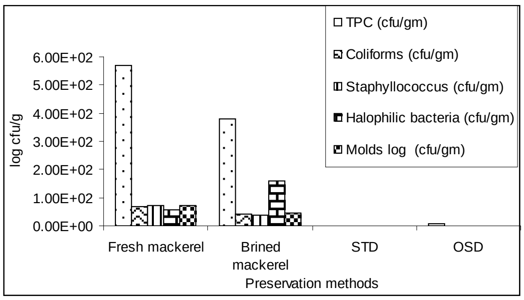

Figure 7 Variation of microbial properties of fresh, brined and dried mackerel

4.3 Effect on sensory properties

The regression coefficients for sensory attributes of drying method with their coefficients of determination *(R^2)* showed that the STD method, all the sensory responses except odor gave R^2>0.900. The R^2 values obtained from the experimental dryer was statistically adequate for prediction. [33] has stated that R^2>0.75 can be used for prediction purpose. Analysis showed the STD drying method has significant effects (P<0.05) on taste, texture, odor, appearance, and overall acceptability scores. Figure 8 shows a contour plot of overall acceptability scores of STD and OSD dried mackerel, for all sensory attributes examined; panelists preferred fish dried with STD. The optimum points for all attributes evaluated were at temperatures ranging from 40-46 ^{o}C for 18-29h.

The overall acceptability scores decreased significantly (P<0.05) with increasingly storage period at ambient temperature. On correlating the mean panel scores for overall acceptability of dried mackerel, STD had a shelf-life of 154 days at ambient temperature, while OSD mackerel had <98 days (Fig.9).

During storage of dried mackerel, the surface of the open sun dried mackerel became damp showing that the fish had higher moisture content. This can be due to the breakdown of fish muscles releasing moisture and moisture uptake from the surroundings, which might be responsible for the damp formation on the dried fish surface [34]. Serafica and Mundo [35] studied qualitative performance of a solar dryer for fish and found similar quality results.

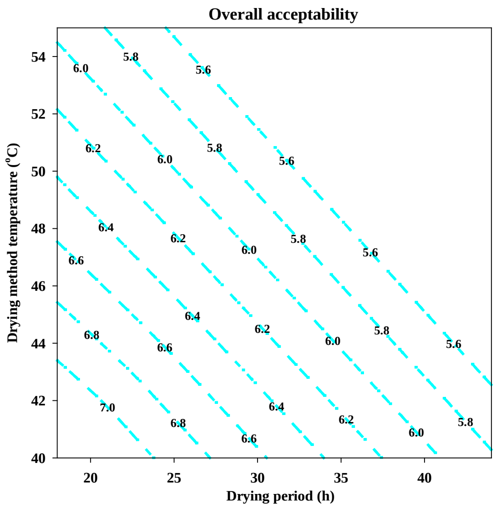

Figure 8 Contour plot on the effect of drying temperature and time on overall acceptability response in STD dried mackerel (Temperature 40-46 °C=STD)

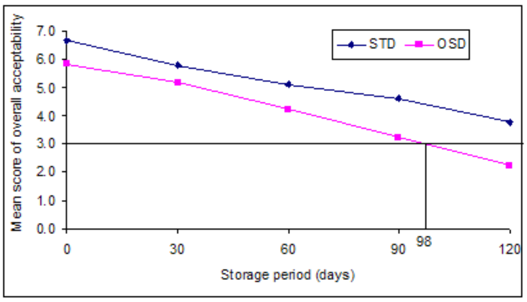

Figure 9 Overall acceptability of tunnel dryer dried mackerel during storage at ambient temperature

Drying method	Constant		R^2	Shelf-life (days)
OSD	Y = 5.959	-0.0303x	0.9943	98
STD	Y = 6.582	-0.0233x	0.9937	154

4.4 Financial analysis for solar tunnel dryer

Financial analysis was calculated (Table 4) for drying of mackerel using the existing STD at Energy Park, AIT. The life span of the solar dryers is 10 years. The drying capacity of a dryer is 100 kg fresh mackerel in a single batch. Other financial information was obtained from the district central co-operative bank, Maharashtra, India for a small scale loan up to 500,000 INR at an interest rate of 6%. In India, the marine capture fisheries are closed every year during monsoon period (June-September) for breeding the marine fishes. Therefore, the STD can be operated for eight months in every year for mackerel drying. Only 32 batches of fish were dried, and in one batch 35 kg dried fish were produced. The preservative treatment (common salt) is 1:4 ratio of the fresh weight of mackerel (17.5 kg of NaCl) for each batch of 100 kg fresh fish [36]. Other assumptions were used: the cost increments for labor 10%, maintenance 5%, packaging 5%, fresh mackerel 2.5%/kilogram, preservative 2.5%, selling cost for dried mackerel at 5% per year. The cost of fresh mackerel is 15 INR/kg and selling cost of dried mackerel is 80 INR/kg [37].

Figure 10 shows the cash flow of the STD drying method. The dried mackerel weight in STD is less than the weight ratio of the existing drying practice along the coast of India. Where quality is concerned,

Table 4 Capital cost and annual expenditure of dry fish production in STD in Indian conditions (1 US$= 45.00 INR)

Particular Cost		Cost (INR)
Capital cost	=	45,000
Maintenance cost	=	720
Labor charges	=	6,400
Packaging cost	=	280
Fresh mackerel cost	=	48,000
Preservatives Cost	=	2,000
A. Total annual cost	=	57,400
B. Income from sales of dried mackerels	=	89,600
Annual Net Income of first year (B-A)	=	32,200

the quality of experimental dried mackerel is better than the existing drying practice. Therefore, the fish dried in an experimental dryer will fetch a higher selling price, compared to the open sun dried fish. It is also suggested that the economic analysis a solar dryer should also incorporate the cost benefits due to improved quality, higher yields, less floor area, and quicker drying [38]. There are important differences between the existing fish drying practice and the experimental drying method. The final moisture content of experimental dried mackerel is <17% (wb), while moisture content was 32% (wb) of the existing fish drying method (OSD) in India. The STD can dry within 27 h. The net present worth (NPW) is the difference between the present worth of all cash inflows and outflows of experimental dryers [39]. Cash outflow is only at the beginning of the project in the STD drying method. This indicates that the present experimental dryer is financially viable for installation. The financial analysis showed that the average net income/year (for 10 year) is about 45,223 INR and the pay-back period is also less than 1.5 years.

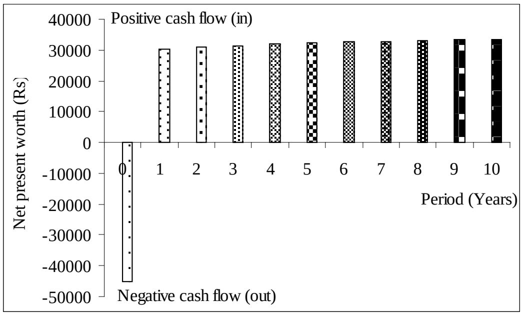

Figure 10 Cash flow for solar tunnel dryer

5. Conclusions

The results of mackerel drying in cabinet dryers showed that, the *Midilli* model was found to give the best fit and could be used to precisely predict the moisture content of dried mackerel in a solar tunnel dryer. The drying of fish in the STD was distinctly faster than the OSD. The overall drying efficiency of the STD is estimated to be 19.87% during fish drying. The biochemical quality of dried mackerel was within the acceptable limits during the 120 days storage period. The total bacterial count increased very slowly with storage period but was within acceptable limits. The fish dried in the STD had softer texture, and had good odor and a bright attractive color. On the other hand, the fish dried in the open sun showed rough texture, fishy odor, and whitish yellow patches on the surface. Financial analysis shows that the use of an STD is viable and profitable; the pay back period is 1.5 years. A net average income of about 45,223 INR can be obtained per year for 10 years for the STD. Therefore, the study suggests that the current experimental dryers design could be used to produce quality dry fish products and thus, may help the fish producer in achieving high quality dry fish products with more net income.

6. Nomenclature

a, b, c, g, h, n	Empirical drying model constants
AOAC	Association of Official Analytical Chemists
a_w	Water activity
cfu	Colony forming unit
EMC	Equilibrium moisture content
FFA	Free fatty acid
INR	Indian Rupees
K, k_o, k_1	Empirical coefficients in the drying models. (h^{-1})
m.c.	Moisture content
MR	Moisture Ratio
NaCl	Sodium chloride
NPW	Net present worth
OSD	Open sun drying
PV	Peroxide value, Photo voltaic panel
RH	Relative humidity
RSM	Response Surface Methodology
Rs	Rupees

RMSE	Root-Mean-Square Error
STD	Solar tunnel dryer
SPSS	Statistical Package for the Social Sciences
TBA	Thiobarbituric acid
TMA	Trimethylamine
TMAO	Trimethylamine oxide
TMA-N	Trimethylamine nitrogen
TPC	Total plate count
TVB-N	Total volatile bases nitrogen
w.b.	Wet basis

7. References

[1] Gopakumar, K., Low cost technologies and their application in fish processing, Quality control in fish processing. Asian productivity organization, pp. 16-43, 2002.

[2] Arata, A. and Sharma V., Performance evaluation of solar assisted dryers for low temperature drying applications, J. Renew. Energy, Vol. 5-6, pp. 729, 1991.

[3] Ratti, C. and Mujumdar, A., Solar Drying of Foods: Modeling and Numerical Simulation, Sol. Energy, Vol. 60, No. 3-4, pp. 151, 1997.

[4] Kumar, S. and Bhattacharya, S.C., Technology Packages: Solar, Biomass and Hybrid Dryers, Renewable Energy Technologies in Asia, A Regional Research and Dissemination Programme, pp. 44-60, 2005.

[5] Jain, D. and Pathare, P.B., Study of drying kinetics of open sun drying of fish, J. Food Eng. Vol. 78, No. 4, pp. 1315-1319, 2007.

[6] Sankat, C. K. and Mujaffar, S., Sun and solar cabinet drying of salted shark fillets, Proceedings of the 14th International drying symposium, Brazil, August 22- 25, pp. 1584-1591, 2004.

[7] AIT, Solar tunnel dryer, construction manual, Report submitted to Swedish international cooperation development agency. SERD, Energy Program, AIT, Thailand, 1997.

[8] Leon, M.A., Kumar, S. and Bhattacharya, S.C., A comprehensive procedure for performance evaluation of solar food dryers, Renew. and Sust. Energy reviews, Vol. 6, pp. 367-393, 2002.

[9] Ben Mabrouk, S. and Belghith, A., Simulation and design of tunnel dryer, Renew. Energy, Vol. 5, No. 1, pp. 469-473, 1994.

[10] Cassini, A.S., Marczak, L.D.F. and Norena, C.P.Z., Drying Characteristics of Textured Soy Protein: A Comparison between Three Different Products, Drying Technology, Vol. 25, pp. 2047-2054, 2007.

[11] Akpinar, E.K., Bicer, Y. and Midilli, A., Modeling and experimental study on drying of apple slices in a convective cyclone dryer, J. Food Process Eng. Vol. 26, No. 6, pp. 515-541, 2003.

[12] Ilhan, C., Aktas, M. and Hikmet, D., Mathematical modeling of drying characteristics of tropical fruits. Applied Thermal Eng.27, pp. 1931-1936, 2007.

[13] Zhang, G.C., Study on heat pump dried shrimp and fish cake, Dalian Fisheries University, China. The UNU, fisheries training program. Final project report, pp. 40, 2004.

[14] Henderson, S.M., Progress in developing the thin layer drying equation, Transactions of the ASAE, 17, pp. 1167-1172, 1974.

[15] Sharaf, EYI., Blaisdell, J.L. and Hamdy, M.Y., A model for ear corn drying, Transactions of the ASAE, 5, pp. 1261-1265, 1980.

[16] Waewsak, J., Chindaruksa, S. and Punlek, C., A Mathematical Modeling study of hot air drying for some agricultural products,

Thammasat Int. J. Sci. and Tech., Vol.11, No. 1, pp. 14-20, 2006.

[17] Yaldiz, O., Ertekin, C. and Ibrahim, U.H., Mathematical modeling of thin layer solar drying of sultana grapes, Energy, Vol. 26, pp. 457-465, 2001.

[18] Verma, L.R., Bucklin, R.A., Endan, J.B. and Wratten, F.T., Effect of drying air parameters on rice drying models, Transactions of the ASAE, Vol. 28, pp. 296-301, 1985.

[19] Karathanos, V.T. and Vasilios, G.B., Application of a Thin-Layer Equation to Drying Data of Fresh and Semi-dried Fruits, J. Agri. Eng. Res. Vol. 74, No. 3, pp. 355-361, 1999.

[20] Midilli, A. and Kucuk, H., Mathematical modeling of thin layer drying of Pistachio by using solar energy, Energy Convers Manage, Vol. 44, No. 7, pp. 1111-1122, 2003.

[21] Association of Official Analytical Chemist, Fish and other marine products, AOAC official methods of analysis, 35 pp. 1-35, 2000.

[22] Andrews, W.H., Microbiological methods. AOAC official methods of analysis, 17, pp. 1-57, 2000.

[23] Filsinger, B.E., Sisti, E. and Bergamaschi, N.J., Technical note: Chemical and sensory assessments in ripened anchovies, Int. J. Food Sci. Tech. Vol. 22, pp. 73-76, 1987.

[24] Pedrosa-Menabrito, A.P. and Regenstein, J.M., Shelf-life extension of fresh fish, A review part III. Fish quality and methods of assessment. J. Food Quality, Vol.13, pp. 209-531, 1990.

[25] Council Regulations, In Diario Oficial de las Comunidades Europeas, No. L 5/21: 5-6. Brussels, Belgium: European Commission, 1989.

[26] Bala, B.K. and Mondol, M.R.A., Experimental investigation on solar drying of fish using solar tunnel dryer, Drying Technology, Vol. 19, No. 2, pp. 427-436, 2001.

[27] Togrul, I.T. and Dursun, P., Mathematical modeling of solar drying of apricots in thin layers, J. Food Eng. Vol. 55, pp. 209-216, 2002.

[28] Richards, M.P., Kelleher, S.D. and Hultin, H.O., Effect of washing with or without antioxidants on quality-retention of mackerel fillets during refrigerated and frozen storage, J. Agri. and Food Chemistry, Vol. 46, No.10, pp. 4363-4371, 1998.

[29] Connell, J.J., Control of fish quality, Fishing news books. Blackwell scientific publication, pp. 1-3, 1990.

[30] Srikar, L.N., Khuntia, B.K., Reddy, G.V.S. and Srinivasa, B.R., Influence of storage temperature on the quality of salted Mackerel (*Rastrilliger kangurta*) and pink perch (*Nemipterus japonicus*). J. Sci. and Food Agri., Vol. 63, pp. 319-322, 1993.

[31] US Food and Drug Administration. Center for Food Safety and Applied Nutrition, Fish and fisheries products hazards and controls guidance. 3rd edition. Retrieved June, 2002.

[32] Lupin, H.M., Boeri, R.L. and Moschiar, S.M., Water activity and salt content relationship in most salted fish products, J. Food Tech., Vol. 16, pp. 31-38, 1981.

[33] Henika, R.G., Use of response surface methodology in sensory evaluation, Food Tech. November, pp. 96-101, 1982.

[34] Giyatmi, A.P., Fawzya, Y.N. and Ariyani, F., Salting and drying of mackerel (*Rastrilliger kangurta*), ASEAN Food J., Vol. 7, No.3, pp. 141-146, 1992.

[35] Serafica, E., Mundo, D.R., Design and qualitative performance of a hybrid Solar-biomass powered dryer for fish, Renewable Energy Technologies in

Asia, A Regional Research and Dissemination Programme, 2005.
[36] Gopakumar, K., Dried and smoked fish products, Fish drying and smoking production and quality, Technomic publication, pp. 47-87, 1998.
[37] Department of Fishery, Annual statistical report, Government of Maharashtra, India, 2007.
[38] Sitthiphong, N., Anupong, H., Wiwat, K., Pradit, T. and Teera, S., Multi-Crop Dryers Project First Phase final report submitted to The International Development Research Centre (IDRC) of Canada by Chiang Mai University, Thailand, 1989.
[39] Hollick, J.C., Commercial scale solar drying, Renew, Energy, Vol.16, pp. 714-719, 1999.