Chapter 5
Results and Discussion

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This chapter presents the results of the experiments conducted to study the drying air conditions, drying kinetics of ginger and turmeric, comparative performance, effects of drying on texture, colour, rehydration characteristics, volatile oil, oleoresin content and curcumin content of turmeric.

5.1 Drying air conditions through solar collector

Changes of drying air conditions such as ambient temperature, humidity and drying time depend on the design of solar collector, solar radiation trapping mechanism. In the present study, in order to trap the maximum solar radiation and thereby increase the intensity of incident ray as well as the effective drying time, solar collectors were designed in three stages such as simple flat plate collector, fixed compound parabolic concentrator (CPC) and CPC with manual tracking facility since, instant fall of temperature after 2.00 to 2.30 pm due to change of direction of Sun and the effective drying time and temperature were affected. Horizontal and vertical tracking were incorporated on receiver by 11.54^0 C and 4.68^0 C, respectively. After facilitation of solar tracking, the duration of effective temperature was increased by 1.5 hours more than the earlier. The observations recorded for simple flat plate collector (Design stage-I), fixed CPC (Design stage-II) and manual tracking CPC (Design stage-III) are presented in Table 5.1, 5.2 and 5.3, respectively.

The highest temperature in the Design stage I, II and III were recorded to be 33^0 C, 46^0 C, 53.1^0 C over ambient of 25.5^0 C, 35^0 C and 38.4^0 C, respectively. The average temperature rise over ambient during the study period in the Design stage I, II and III were observed to be 5.9^0 C, 9.5^0 C and 11.2^0 C, respectively. In the Design Stage II and III, the average rise of temperature were found about 37.72% and 47.2%, respectively more than the Design stage-I i.e simple flat plate collector.

Table 5.1.Observed drying air conditions using flat plate solar collector (Design stage-I)

Max Ambient temp(^{0}C)	Ambient RH %		Collector temp (^{0}C)	Increase in temp (^{0}C)	Average (^{0}C)
	Max	Min			
26.0	61	36	32	6.0	
24.5	64	35	31	6.5	
25.0	66	36	30	5.0	5.917
25.5	64	41	33	7.5	
23.5	67	43	29	5.5	
26.0	67	36	31	5.0	

Table 5.2. Observed drying air conditions using fixed compound parabolic concentrator solar collector (Design stage-II)

Max Ambient temp(^{0}C)	Ambient RH %		Collector temp (^{0}C)	Increase in temp (^{0}C)	Average (^{0}C)
	Max	Min			
30	97	81	39	9	
30	96	68	37	7	
33	93	71	43	10	
34	98	71	44.5	10.5	9.5
36	96	70	45.9	9.9	
35	98	71	46	11	
35	94	90	44	9	

Table 5.3. Observed drying air conditions using manual tracking compound parabolic concentrator solar collector (Design stage-III)

Day	Time	Ambient Temp (^{0}C)	Ambient RH %		Collector Temp (^{0}C)	Increase in Temp (^{0}C)	Average (^{0}C)
			Max	Min			
1	10.30	35.0	73	42	44.0	9.0	
	12.30	37.2			48.0	10.8	
	16.00	35.0			44.5	9.5	
2	10.30	38.2	70	30	52.4	14.2	11.2 ^{0} C
	12.00	38.4			53.1	14.7	
	16.00	35.0			44.0	9.0	

A small solar dryer with limited sun tracking capabilities was designed and tested (Mwithiga and Kijo, 2006). The dryer had a mild steel absorber plate and a polyvinyl chloride transparent cover and could be adjusted to track the sun in increments of 15^0. Prasad *et al.* (2006) observed that at no-load conditions a roof that is more inclined toward

the vertical plane leads to an increased airflow in chimney dependent solar dryers. The experimental results of the developed drying system are found to be in conformity to others which have been published in the area of solar energy based drying systems viz. Afriyia *et al.*(2009); Bennamoun and Belhamri (2003).

5.2 Drying kinetics of ginger and turmeric

Drying kinetics study was done to understand the drying kinetics of thin layer drying of ginger and turmeric rhizome those were sliced and dried in a series of experiments. Moisture content of products differs according to the tray positions (Prasad *et al.*, 2006). Drying experiments of ginger and turmeric rhizomes were carried out by interchanging the trays in a predetermined logical sequence and time interval for near uniform drying. The sequencing was done in a matrix manner (Table 5.4). The results of variation of moisture content with respect to time and interchanging of tray positions for drying of ginger and turmeric slices are presented in following sections.

Table 5.4 Matrix of tray interchange followed in IDS

Tray positions					
6	5	4	3	2	**1**
5	4	3	2	**1**	6
4	3	2	**1**	6	5
3	2	**1**	6	5	4
2	**1**	6	5	4	3
1	6	5	4	3	2

5.2.1 Drying kinetics of ginger

Drying air temperature was in the range of 47-55^0 C and air velocity measured, was between 1.0 to 1.3 m/s. Initial drying was carried out through solar drying alone followed by burning of paddy husk in the combustion chamber. Average solar intensity during experimentation was 456.601W.m^{-2}. The initial moisture content of ginger was 88.13%. The tray wise variation of moisture content and moisture ratio against time are presented in Table 5.5 and Table 5.6, respectively. During the initial period of drying, the drying rate was high in the bottom most tray (T_I) in comparison to other trays because of exposure to higher temperature (Fig.5.1). Initially the drying rate was significantly high for all the trays until the average moisture content got reduced to the range of 60-70% (wb). At the end of

four hours of drying the moisture contents were reduced to 45.23, 46.0, 42.0, 50.5, 58.0, and 62.7 % (wb), for ginger placed in the six trays (T_I, T_{II}, T_{III}, T_{IV}, T_V, T_{VI}) starting from bottom to top, respectively.

Table 5.5 Tray wise moisture content variation with time during drying of ginger

Time, h	Moisture content, %					
	Tray1	Tray 2	Tray3	Tray4	Tray5	Tray6
0.0	88.13	88.13	88.13	88.13	88.13	88.13
1.0	74.40	77.10	79.80	84.20	85.60	86.10
2.0	55.90	62.00	64.00	72.00	77.83	80.90
4.0	45.23	46.00	42.00	50.50	58.00	62.70
7.0	27.11	24.90	23.00	30.60	34.11	40.00
8.5	18.67	19.50	18.00	21.33	20.20	28.30
10.0	13.03	15.89	15.00	13.66	14.00	16.60
12.0	10.19	12.10	11.00	10.20	9.86	10.80
16.0	7.05	7.70	8.00	7.70	7.20	8.36

Table 5.6 Tray wise variation of moisture ratio with time during drying of ginger

Time, h	Moisture ratio, ln (MR)					
	Tray1	Tray2	Tray3	Tray4	Tray5	Tray6
0	0	0	0	0	0	0
1	-0.1854	-0.1461	-0.1083	-0.0497	-0.0317	-0.0253
2	-0.5063	-0.3887	-0.3530	-0.2217	-0.1358	-0.0933
4	-0.7524	-0.7325	-0.8407	-0.6233	-0.4642	-0.3761
7	-1.3948	-1.5113	-1.6235	-1.2348	-1.0962	-0.8995
8.5	-1.9390	-1.8703	-1.9982	-1.7337	-1.8158	-1.3373
10	-2.5993	-2.2111	-2.3166	-2.4999	-2.4501	-2.1343
12	-3.2360	-2.7668	-3.0098	-3.2329	-3.3452	-3.0611
16	-7.3918	-4.7527	-4.3961	-4.7527	-6.0055	-4.0886

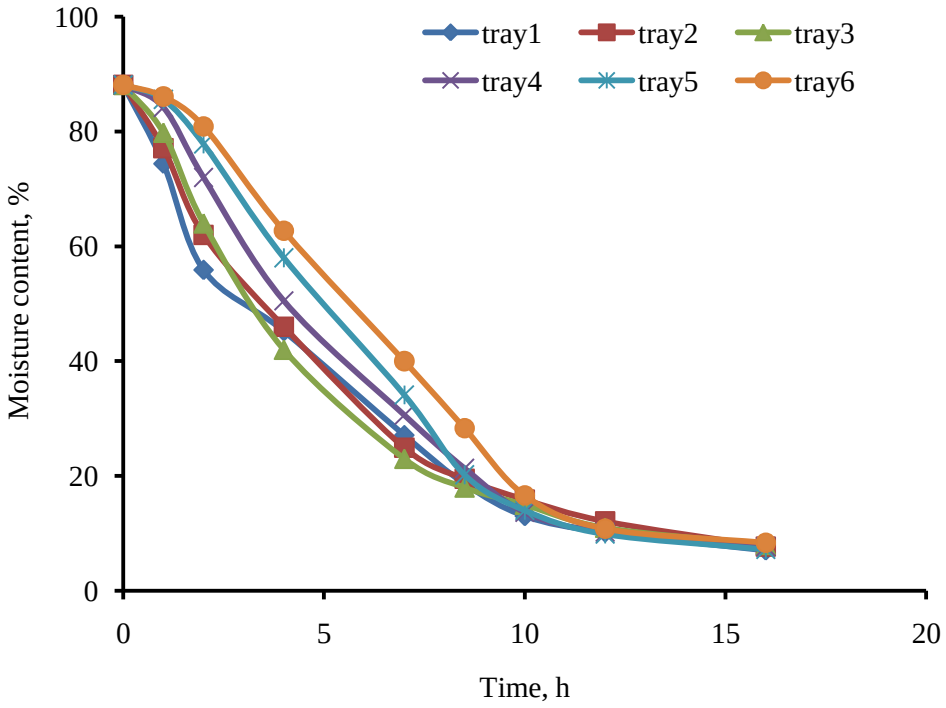

Fig. 5.1 Variation of tray wise drying curve of ginger in IDS

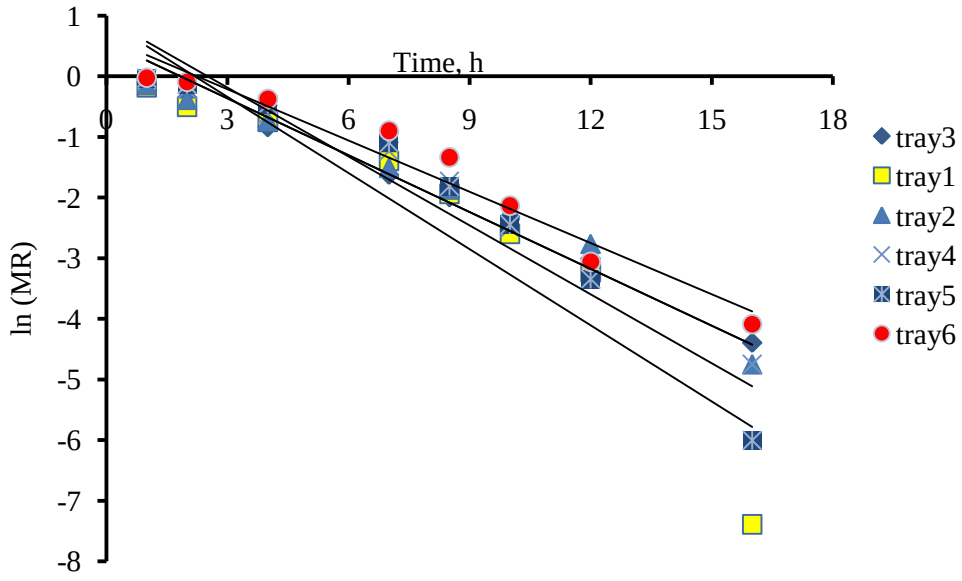

Fig. 5.2 Variation of drying rate constant against time of ginger drying in IDS

Variation in drying rate constant with respect to tray positions against time of drying are represented in Fig.5.2. Higher value of drying rate constant as well as wide variation is undesirable from quality aspects of biological materials. In a study to investigate the effect of drying rate constant on head rice yield reduction of rice, a value of 0.23 h^{-1}, significantly controlled broken percentages regardless of drying duration (Chen *et al.*,1997). The slope of the trend lines representing drying rate constants varied between 0.281 h^{-1} and 0.481 h^{-1} among the trays in the present case. As the drying air travels upward in the cabinet dryer, the relative humidity got increased in the successive trays resulting in reduced drying rates for the same period of time. Therefore, at the stage of 60-70% moisture content (i.e. after four hours) ginger trays were interchanged to get uniform drying rate. At the end of 16^{th} hour, drying was almost complete and the moisture contents (% wb) of the trays T_I to T_{VI} were 7.05, 7.7, 8.0, 7.7, 7.2 and 8.36, respectively. It was observed that tray positions affected rate of drying to a certain level at the beginning, but eventually the rate was uniform in all the trays towards the end of drying as evident from the drying curves.

5.2.2 Drying kinetics of turmeric

It was observed that rate of evaporation in all the trays were near uniform during ginger drying experimentation as a result of sequencing of trays as per matrix followed. Hence, while drying turmeric instead of considering the entire six trays only one tray was monitored.

Assuming equivalent moisture as 6 %, MR was calculated as follows:

$$MR=(MC-6)/(IMC-6)x100$$

Where, MR = moisture ratio

MC = moisture content, % (wb)

IMC = Initial moisture content, % (wb)

Results of the experiments are presented in Table 5.7. It could be seen that drying was accomplished in 14 hours of effective drying. The moisture content was brought down to 6.26% (wb) from initial level of 89.26% (wb). Drying curve of turmeric is graphically represented in Fig. 5.3. The curve described here, are comparable, in terms of shape, to those reported by Andres *et al.*(2004), who described the drying rate behaviour of apple

slices subjected to combined microwave and air drying. Entire drying was in falling rate period. Similar results have been presented for red chillies (Shivhare *et al*., 1995; Chandy *et. al*., 1992) and for green chillies (Ahmed and Shivhare, 2001). Moisture content dropped down to 22.63 % (wb) in first 7 h which was 74.64% of total the moisture. During the remaining 7 h 19.35% of total moisture got evaporated. Curve of ln(MR) versus time was drawn (Fig. 5.4). Drying rate constant value was found to be 0.411 h^{-1} which is near similar to values for ginger.

Table 5.7 Variation of moisture with time (turmeric)

Time, h	MC(%)	MR	ln(MR)
1	82.05	0.9134	-0.0906
3	59.82	0.6464	-0.4363
5	34.19	0.3386	-1.0830
7	22.63	0.1997	-1.6108
9	16.01	0.1202	-2.1184
11	10.85	0.0583	-2.8430
13	6.71	0.0085	-4.7645
14	6.26	0.0031	-5.7690

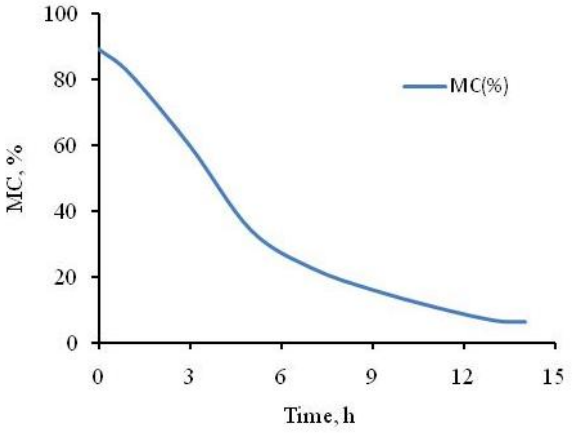

Fig. 5.3 Drying curve of turmeric in IDS

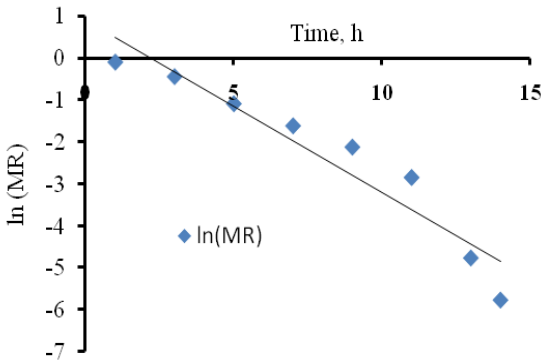

Fig. 5.4 Drying rate constant against time of turmeric drying in IDS

5.3 Simulated and optimized drying process

In study by Kaleemullah and Kaillapan (2005), the average moisture ratio of chilies at various temperatures was fitted in four models to estimate values of the model parameters. Simulation of the drying method in the IDS was done by using different thin

layer drying models based on the moisture ratio of samples as stated in the previous chapter. Tray wise moisture content data were converted into the moisture ratio (MR) expressions and curve fitting with drying time for the selected drying models were analyzed.

5.3.1 Ginger drying

Relevant model parameters for ginger were determined using the experimental value of moisture ratios and are listed in Table 5.8. Graphical representation of experimental MR values of ginger fitted with all the six selected models that were obtained from Sigmaplot software are represented in Fig.5.5 to Fig.5.10. The minimum average value of R^2 was found to be 0.968 among all the models irrespective of tray positions. However, Page model showed highest value of R^2 (0.997) and lowest value of SEE (0.020). Mean percentage error P, was found to be less than 0.0001 for all the cases. Gowen *et al.* (2008) in their study found Page model as best suited to model the dehydration data. Analyses of overall statistical parameters from the present study of drying kinetics for ginger rhizomes also validate Page model as the most suitable one among the six models considered. Experimental and simulated (Page model) moisture ratio curves were drawn (Fig.5.11). It could be seen that the curves were near similar indicating sound drying conditions. This is in agreement with the findings of Doymaz (2005) and Simal *et al*. (2005) who reported that the Page model gave the best model fit for dehydration of green beans and kiwi fruit, respectively.

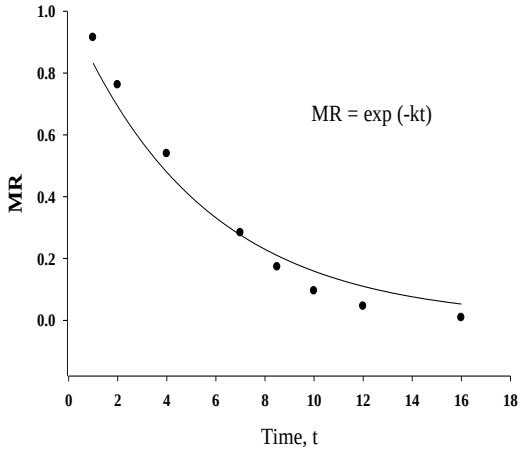

Fig. 5.5 Lewis model

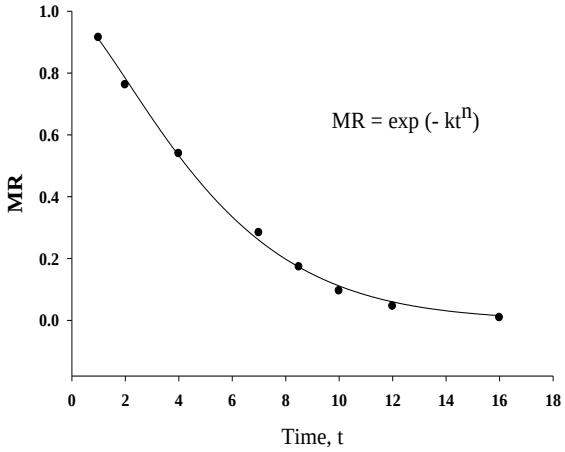

Fig. 5.6 Page model

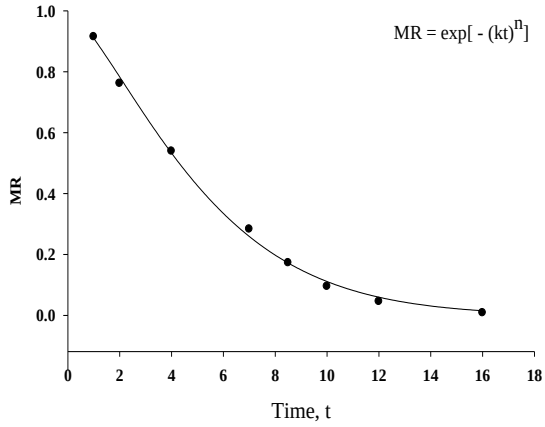

Fig. 5.7 Modified Page model

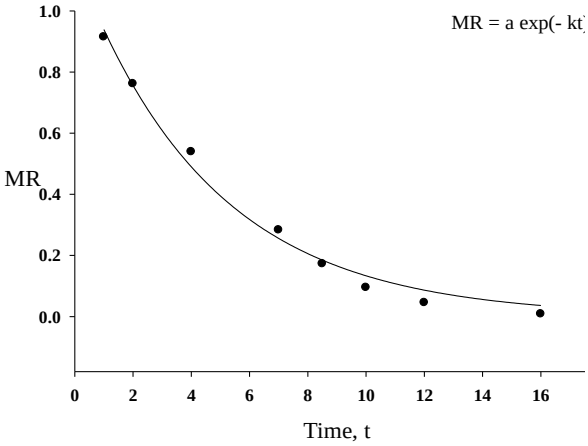

Fig. 5.8 Henderson & Pabis model

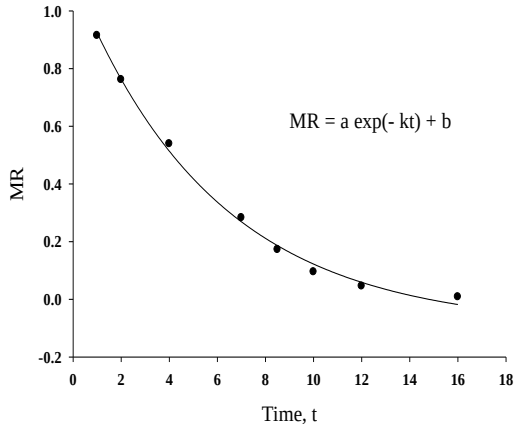

Fig. 5.9 Logarithmic model

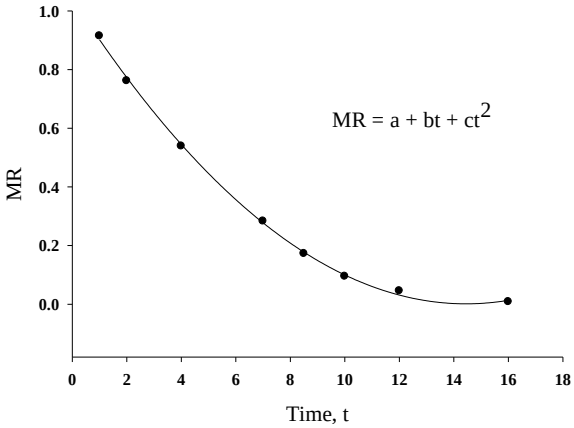

Fig. 5.10 Wang & Singh model

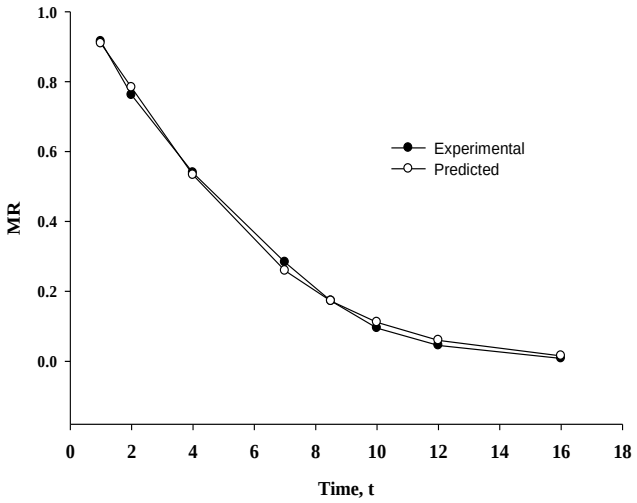

Fig. 5.11 Experimental and simulated MR curves (ginger)against time for best fit Page model

Table 5.8 Estimated values of parameters of different applied models (Ginger)

Model / Av.	Tray No.	Estimated parameters					R^2	SEE
		k	n	a	b	c		
Lewis	1	0.2184					0.9906	0.0355
	2	0.2047					0.9939	0.0290
	3	0.2130					0.9884	0.0413
	4	0.1830					0.9662	0.0735
	5	0.1660					0.9388	0.1029
	6	0.1452					0.9292	0.1085
Average							0.9679	0.0651
Page	1	0.1987	1.0564				0.9901	0.0364
	2	0.1583	1.1505				0.9985	0.0146
	3	0.1447	1.2358				0.9983	0.0156
	4	0.0756	1.4780				0.9977	0.0193
	5	0.0369	1.7944				0.9983	0.0173
	6	0.0251	1.8833				0.9972	0.0214
Average							0.9967	0.0207
Modified Page	1	0.2166	1.0564				0.9831	0.0393
	2	0.2014	1.1505				0.9975	0.0157
	3	0.2093	1.2358				0.9974	0.0168
	4	0.1743	1.4780				0.9967	0.0208
	5	0.1591	1.7944				0.9977	0.0187
	6	0.1412	1.8833				0.9964	0.0231
Average							0.9948	0.0224
Henderson & Pabis	1	0.2239		1.0230			0.9821	0.0404
	2	0.2241		1.0843			0.9960	0.0199
	3	0.2506		1.1570			0.9997	0.0061
	4	0.2237		1.2260			0.9891	0.0379
	5	0.2135		1.2777			0.9702	0.0668
	6	0.1855		1.2623			0.9609	0.0761
Average							0.9830	0.0412
Logarithmic	1	0.1808		1.0501	-0.0723		0.9854	0.0365
	2	0.1990		1.0968	-0.0403		0.9974	0.0159
	3	0.2413		1.1579	-0.0120		0.9998	0.0041
	4	0.1793		1.2640	0.0919		0.9949	0.0259
	5	0.1518		1.3704	-0.1672		0.9828	0.0508
	6	0.1178		1.4409	-0.2586		0.9782	0.0568
Average							0.9898	0.0316
Wang &Singh	1			0.9476	-0.1368	0.0049	0.9844	0.0457
	2			0.9766	-0.1396	0.0050	0.9926	0.0319
	3			0.9907	-0.1481	0.0055	0.9817	0.0445
	4			1.0463	-0.1434	0.0049	0.9944	0.0298
	5			1.0800	-0.1411	0.0045	0.9845	0.0518
	6			1.0839	-0.1256	0.0035	0.9784	0.0598
Average							0.9860	0.0440

5.3.2 Turmeric drying

Representations of experimental MR values of turmeric were also fitted with all the six selected models that were obtained from Sigmaplot software. They are represented in Fig.5.12 to Fig.5.17 and the estimated values of model parameters are presented in Table 5.9.

Table 5.9 Estimated values of parameters of different applied models (Turmeric)

Model	Estimated parameters					R^2	SEE
	k	n	a	b	c		
Lewis	0.2084					0.9573	0.0685
Page	0.0942	1.4604				0.9962	0.0203
Modified Page	0.1983	1.4604				0.9962	0.0203
Henderson and Pabis	0.2508		1.2164			0.9855	0.0400
Logarithmic	0.2048		1.2372	-0.0764		0.9918	0.0301
Wang & Singh			1.0687	-0.1691	0.0067	0.9891	0.0346

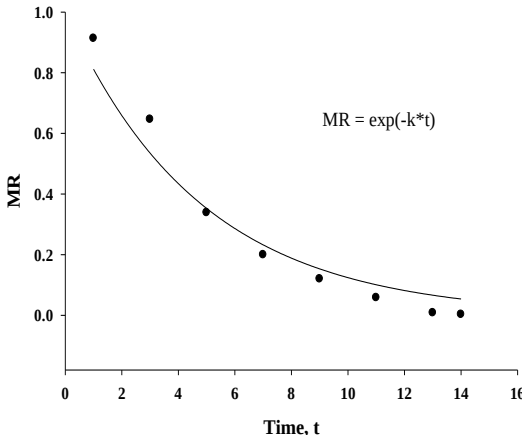

Fig. 5.12 Lewis model

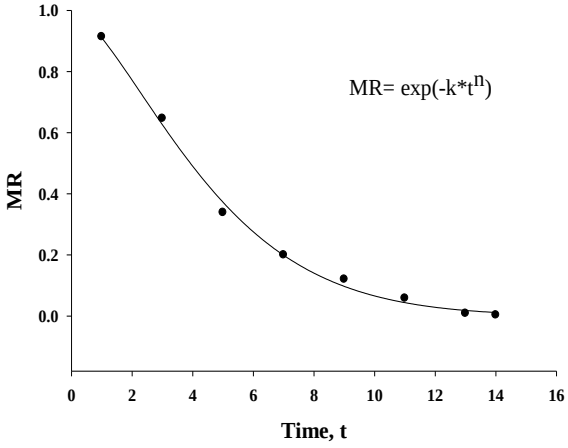

Fig. 5.13 Page model

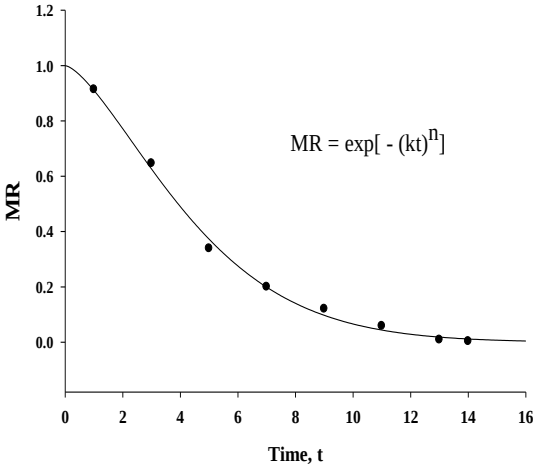

Fig. 5.14 Modified Page model

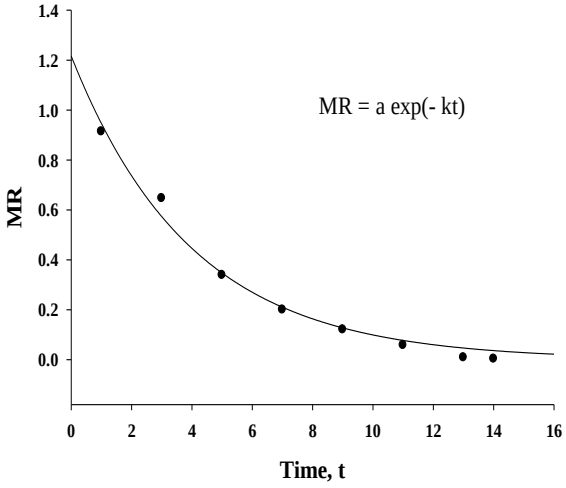

Fig. 5.15 Henderson & Pabis model

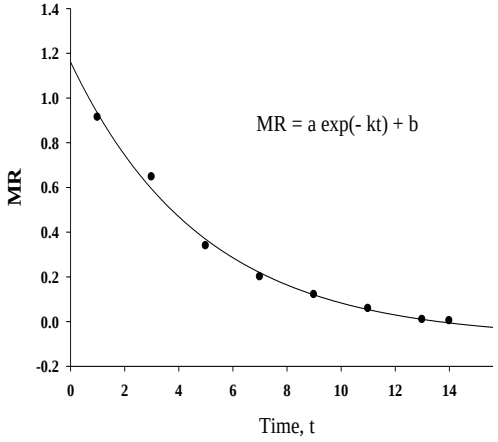

Fig. 5.16 Logarithmic model

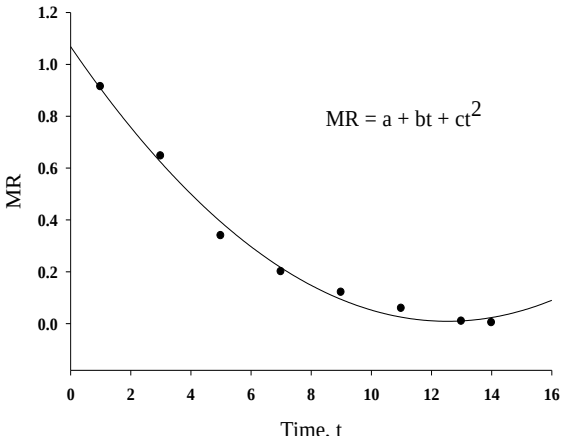

Fig. 5.17 Wang & Singh model

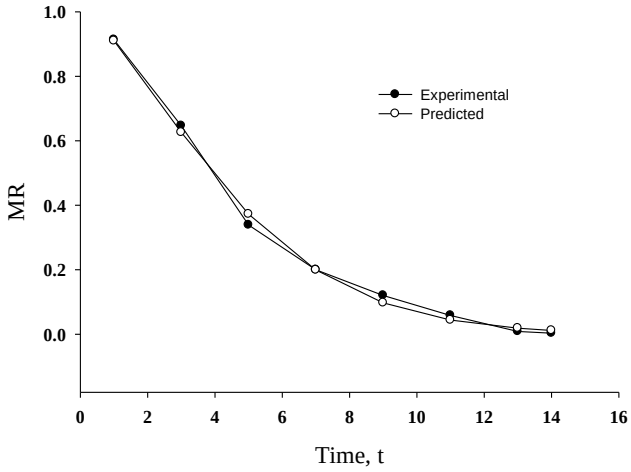

Fig. 5.18 Experimental and simulated MR curves(turmeric) against time for best fit Page model

As in the case of ginger drying, analyses of overall statistical parameters of drying kinetics obtained from drying turmeric rhizomes also validated Page model as the most suitable one among the six chosen models. Experimental and simulated moisture ratio curves were drawn after conducting drying experiments for turmeric (Fig. 5.18) for the best fit model (Page model) and it could be seen that the curves were near similar, again confirming sound drying conditions. In all cases, value of R^2 was greater than 0.90 indicating good fit (Madamba *et al*., 1996; Erenturk *et al*., 2004).

5.4 Effective moisture diffusivity

Diffusivity reflects the capability of moisture evaporation rate of any material to be dried while keeping other drying conditions under control. Madamba *et al.* (1996) have studied the thin-layer drying characteristics of garlic slices. Karathanos and Belessiotis (1999) gave particular attention to the drying of some fresh and semi-dried fruits. Babalis and Belessiotis (2004) found the effective diffusivity, D_{eff} for figs varied from 8.40×10^{-10} to 1.13×10^{-9} m^2/s for the different values of temperature and air velocity. The values were within the general range of 10^{-11} to 10^{-9} m^2/s for food materials (Zogzas *et al.*, 1996). The effective moisture diffusivity during drying for different trays was determined using method of slopes shown in Fig. 5.19 and Fig. 5.20 for ginger and turmeric, respectively.

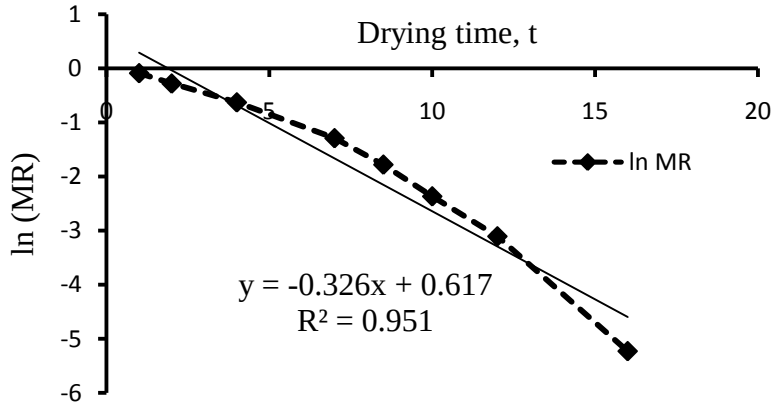

Fig. 5.19 ln (MR) vs. drying time (ginger)

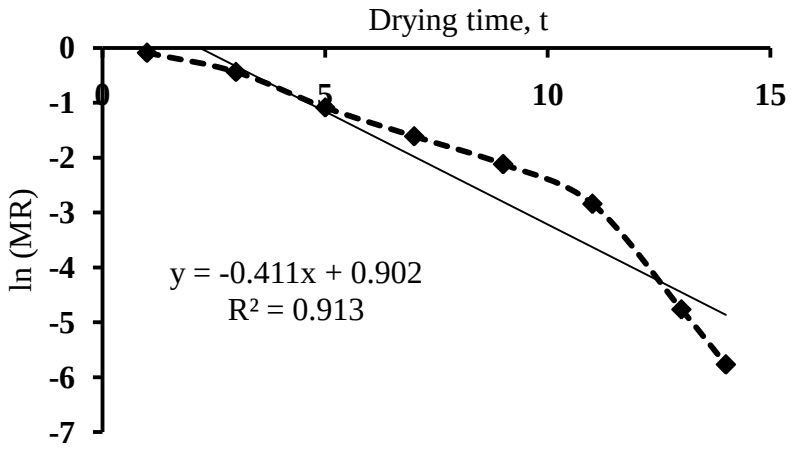

Fig. 5.20 ln (MR) vs. drying time (turmeric)

From Fig.5.19, the slope, k = 0.326 and considering thickness of slices as half of original thickness (slabs), h = 1.5×10^{-3}m, the effective moisture diffusivity (D_{eff}) for ginger using Eqn.4.16 was found to be, 2.97×10^{-7} m^2s^{-1}. While experimenting with turmeric rhizomes the slope from the curve ln(MR) against drying time (Fig. 5.20) was found to be k = 0.411. Due to similarity in size of turmeric with that of ginger slices, h was taken as 1.5×10^{-3} m and again from the same equation effective moisture diffusivity for turmeric was found to be 3.747×10^{-7} m^2s^{-1}. This was in accordance with the observation of Karathanos *et al.* (1990), who observed that simple method of slopes could be used for estimation of diffusivity.

From the results it could be seen that, diffusivity in IDS was 35.7% more in comparison to diffusivity reported in literature under sun drying. Effective moisture diffusivity in case of turmeric drying was nearly 21% more in comparison to ginger drying. Moisture diffusion was easier in turmeric compared to ginger rhizomes probably due its less fibrous nature and blanching treatment. Thus, drying ginger will always be more energy intensive than drying turmeric.

5.5 Comparative performance

The specific energy requirements for individual and combinations of different drying methods namely micro-wave, infrared, vacuum and conventional hot air for drying of mushroom slices were determined and reported that minimum energy was consumed in the micro-wave and maximum energy was in vacuum dryer, respectively (Motevali *et al.*,

2011). Experiments were carried out for drying of ginger and turmeric separately to evaluate the comparative performance of selected drying systems.

5.5.1 Performance evaluation during ginger drying

Experiments to study the comparative performance among IDS, FBD, oven drying and sun drying (control) while reducing the moisture content of ginger from same initial level to nearly same final moisture content were carried out (Fig. 5.21). Drying air temperature in the IDS was between 47 – 55^0 C while using paddy husk as fuel. While using wood stalks during initial system stabilization the same was recorded to be 65^0 C. In FBD and oven drying temperature was maintained within the same range. Comparison of specific energy consumption (Table 5.10) was carried out among the selected mechanical drying systems only. Sun drying was not taken into account as it would vary with location and weather situation leading to improper SEC values. A graphical representation of energy consumed per kg of moisture evaporated in the selected mechanical drying systems is presented (Fig. 5.22). It could be seen that, ginger dried in oven consumed maximum specific energy (75.43 kWh/kg) followed by IDS (33.79 kWh/kg). Lowest SEC was in case of FBD (19.84). However, quality in this case was highly affected. Similar findings have been reported by Tarhan *et al.*, (2010); Martinov *et al.*, (2007) and Doymaz (2006). Assuming 3000 kcal (=3.489kWh) per kg of husk costing Rs.2/-kg, cost of drying was found to be Rs.20/- per kg of moisture evaporated from ginger in IDS. At electrical energy cost of Rs.5/- unit, the same were Rs.99/- and Rs.377/- in FBD and Oven drying, respectively.

Table 5.10 Specific energy consumption: ginger drying

Drying method	Moisture evaporated, Kg	Drying time, h	Energy consumed, kWh	Specific Energy Consumption, kWh/kg
IDS	14.00	24.00	473.02	33.79
FBD	0.38	3.19	7.56	19.84
Oven	2.10	13.20	158.40	75.43

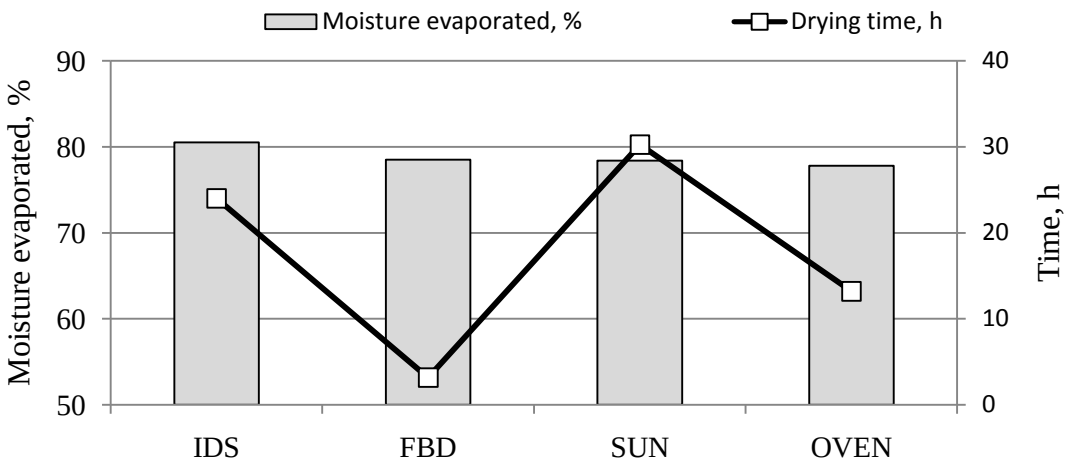

Fig. 5.21 Comparative performance of drying methods (ginger)

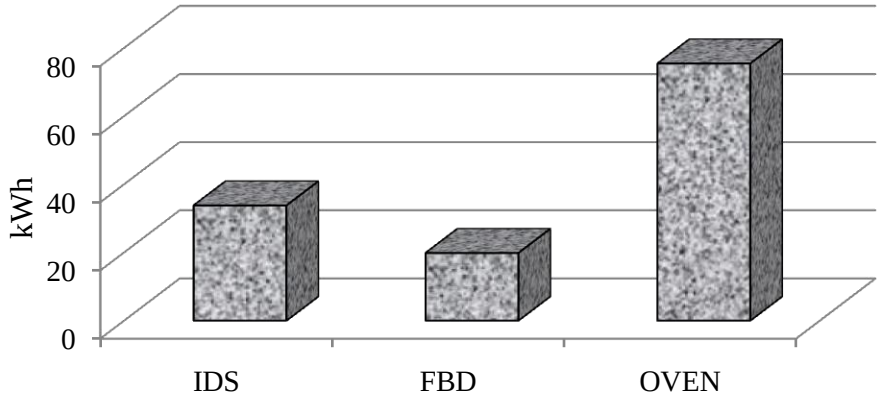

Fig. 5.22 Specific energy consumption (kWh/kg): ginger

5.5.2 Performance evaluation during turmeric drying

Sliced turmeric rhizomes after blanching treatment were dried in the selected drying systems along with sun drying as control. Total moisture evaporated with corresponding time required is presented in Fig. 5.23 to understand the comparative performance. It could be seen that, samples dried in IDS and in oven at a temperature of 55 ± 2^0 C could be dried to nearly same moisture level in same duration. In sun drying, despite taking 5 more hours the moisture evaporation could not be brought down to the same level.

Comparative SEC values are presented in Table 5.11. While comparing the three mechanical drying methods, it was observed that, energy consumption in evaporating per

kg of moisture was highest (18.164 kWh) in oven drying attributing to non uniform exposure of surfaces to the heat supplied. In the IDS, the trays were rotated in a predetermined sequence with stirring of rhizomes at the same time and minimum specific energy consumption of 4.214 kWh/kg was observed (Fig.5.24). Similar findings have been reported by Motevali *et al.*,(2011); Sharma and Prasad, (2006) and Akpinar (2004). Cost of evaporating per kg of moisture were found to be Rs.3/-, 42/- and Rs.90/- in IDS, FBD and Oven drying, respectively.

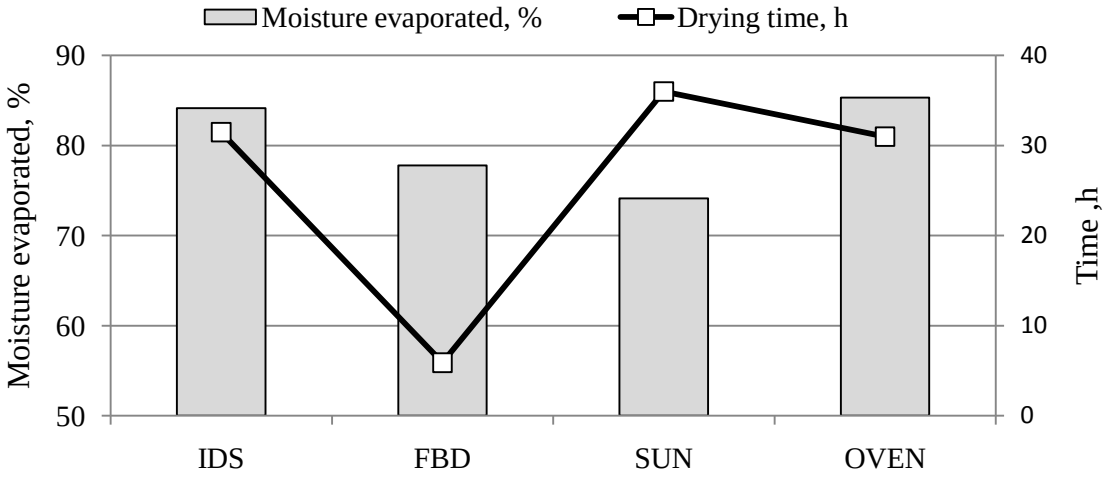

Fig. 5.23 Comparative performance of drying methods (turmeric)

Table 5.11 Specific energy consumption: turmeric drying

Drying method	Moisture evaporated, kg	Drying time, h	Energy consumed, kWh	Specific Energy Consumption, kWh/kg
IDS	27.60	31.50	116.32	4.214
FBD	0.70	5.90	5.91	8.443
OVEN	2.56	31.00	46.50	18.164

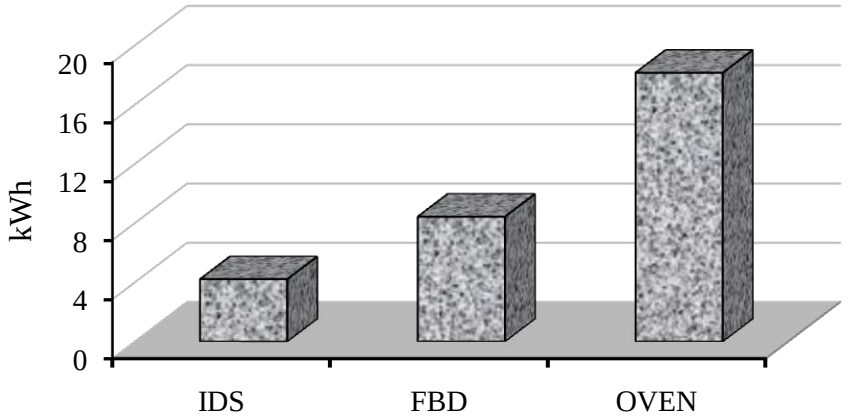

Fig. 5.24 Specific energy consumption (kWh/kg): turmeric

5.6 Status of quality attributes

Different quality attributes of dried ginger and turmeric rhizomes viz. texture, colour, rehydration ratio, oleoresin and volatile oil content, curcumin content and sensory evaluation were carried out.

5.6.1 Ginger quality studies

5.6.1.1 Texture studies of dried ginger

Texture property of dried red peppers obtained from microwave drying was measured as puncture force by Soysal *et al.* (2009), which was a measure of the hardness (N) of the product surface by a texture analyzer using 2 mm cylindrical probe. They have reported that drying temperature, microwave pulse, microwave power output affected the hardness values of red peppers significantly. Cui *et al.* (2003) reported that freeze dried garlic slices were softest followed by microwave–vacuum and air dried garlic slices. Textural properties of dried ginger from all the four drying methods were studied in terms of compressive strength (Fig. 5.25 to 5.29). It was observed that, ginger dried in IDS required minimum force (1124.597 g) among all, indicating controlled and uniform drying in comparison to the other methods where drying was either more severe or non uniform. However, the values differ significantly among different drying methods. Even the value obtained for IDS which was smallest, differed significantly from control which happened to be the highest (1421.62 g).

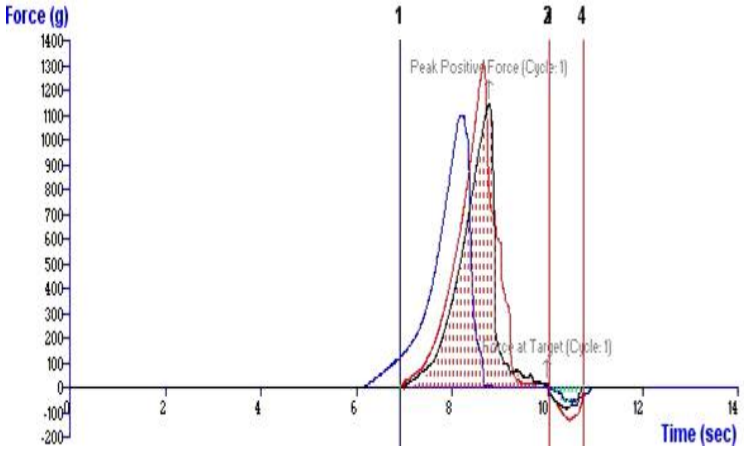

Fig. 5.25 Texture graph of ginger from IDS

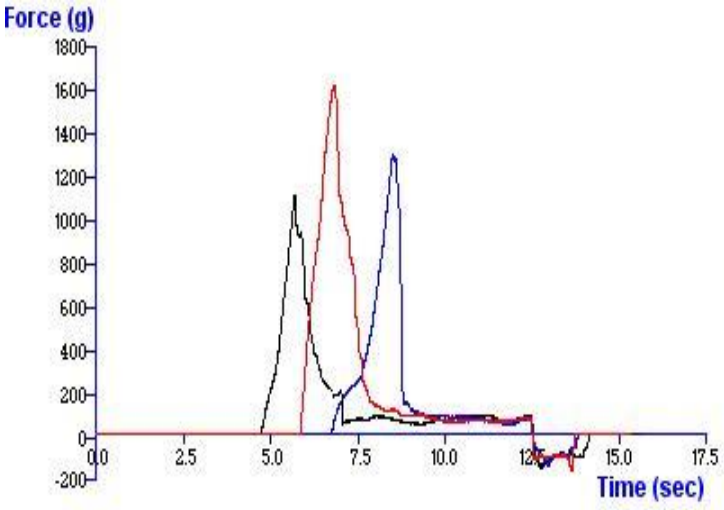

Fig. 5.26 Texture graph of ginger from FBD

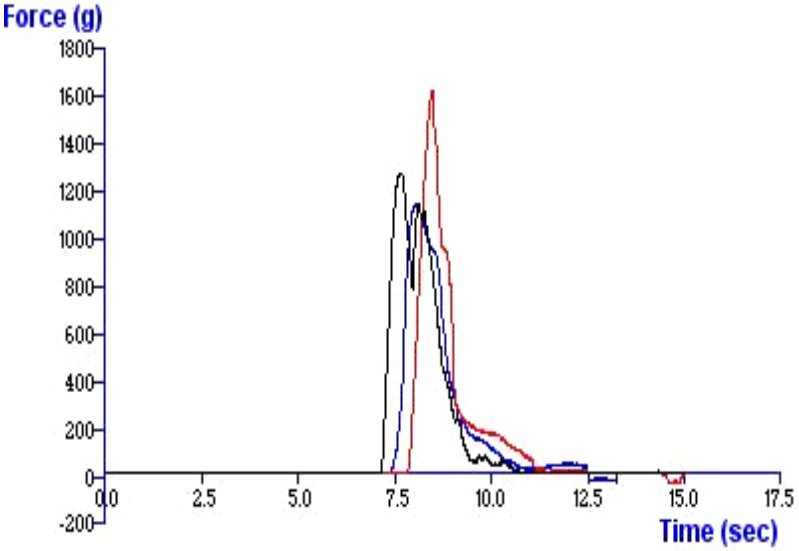

Fig. 5.27 Texture graph of ginger from Oven drying

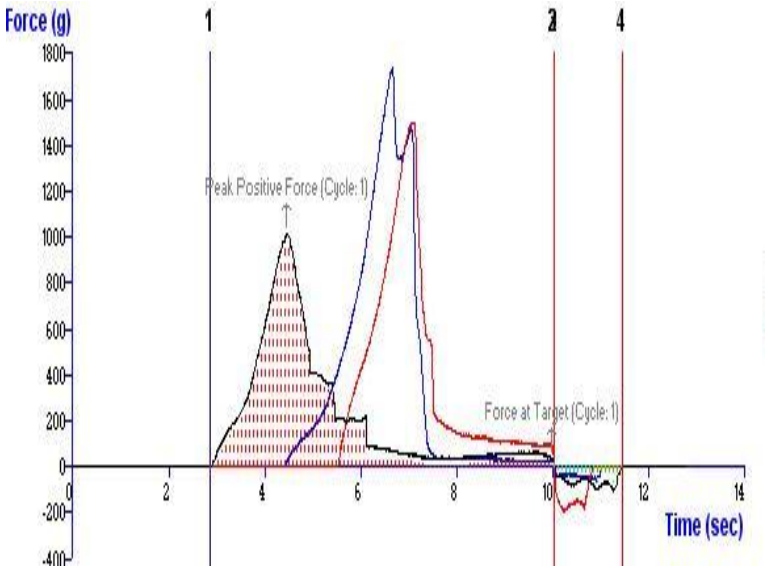

Fig. 5.28 Texture graph of ginger from Sun drying

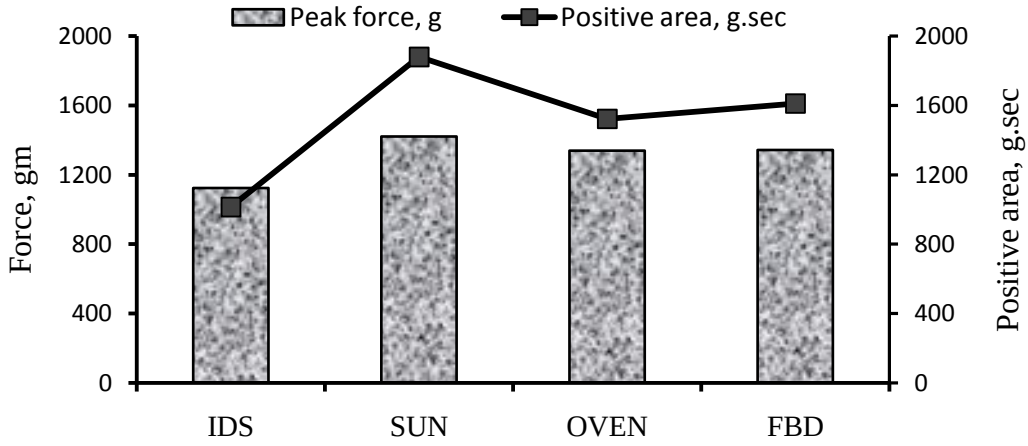

Fig. 5.29 Peak force and Positive area: ginger

Work done to complete a penetration cycle including that to initially rupture the skin, were reflected by positive area under the curves. The total positive area under the curve also reflects toughness of a sample. This measurement effectively records the total 'work' involved in performing this test. It therefore follows that a higher area value indicates a higher amount of energy involved in performing the test and subsequently is

translated as a tougher sample to test. It is evident that IDS produced samples that required smallest peak force as well as positive area under curves, which is a good quality attribute of dried ginger (Fig.5.25). Sun drying being non uniform resulted highest energy requirement to complete the cycle of texture test. Findings are well supported by work done by Krokida and Maroulis (2001a); Lin *et al.,* (1998); Kim and Toledo (1987).

5.6.1.2 Rehydration characteristics of dried ginger

The rehydration characteristics of the dried product are used as a quality index and they indicate the physical and chemical changes during drying and are influenced by processing conditions, sample compositions, sample preparation and extent of structural and chemical disruptions induced by drying (Krokida & Maroulis, 2001a). The rehydration characteristics of dried ginger were studied in terms of RR and COR from 30 to 150 minutes at every half an hour interval. From the results obtained it could be seen that (Fig. 5.30), rehydration ratio values ranged from 1.60 to 2.29 with respect to different time intervals, in case of samples dried in IDS which was compatible with samples from oven drying (2.32) in particular, though they statistically differ significantly. Rehydration ratio of samples obtained from all the four drying methods varried significantly among themselves (Table 5.16). The lowest values were observed in case of FBD, ranging from 1.45 to 2.04 during the respective time intervals. It could also be seen that, rehydration was more rapid during initial 30- 60 minutes and inversly proportional with time. Findings of the study are well supported by work s done by Askari *et al.* (2006), Krokida and Maroulis, (2001b). Higher values of RR is indicative of minimum damage of cells. Non uniform exposure to hot air and extreme drying conditions affects the cell structures resulting in poor rehydration, which is a negative quality attribute. Better values of COR (Fig. 5.31), which is indicative of good quality attributes was observed in products from IDS than from oven as well as sundried. Similar behavior was observed by other authors who experimented different food materials such as green pea, banana, carrot, pumpkin, onion, mushroom, corn, potato, leek, garlic, tomato, pepper, and amaranth grains (Resio *et al*., 2006; Krokida and Philippopoulos, 2005; Planinic *et al*., 2005;).

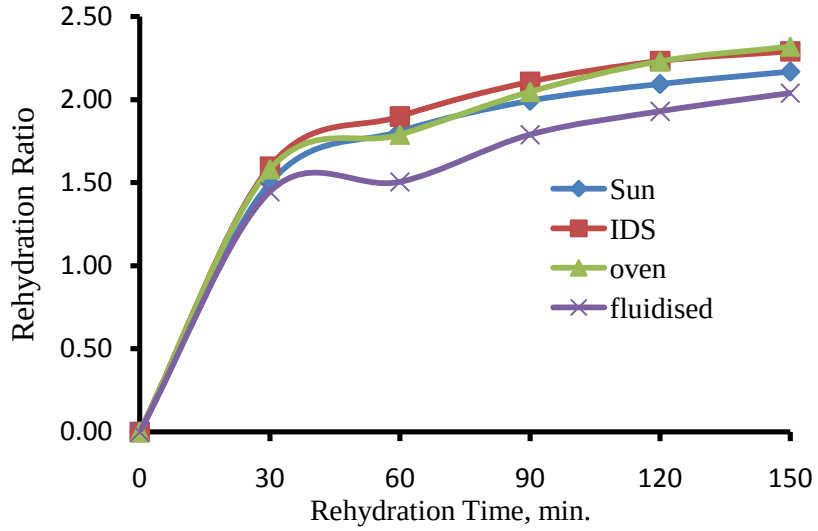

Fig. 5.30 Rehydration Ratio vs Rehydration time

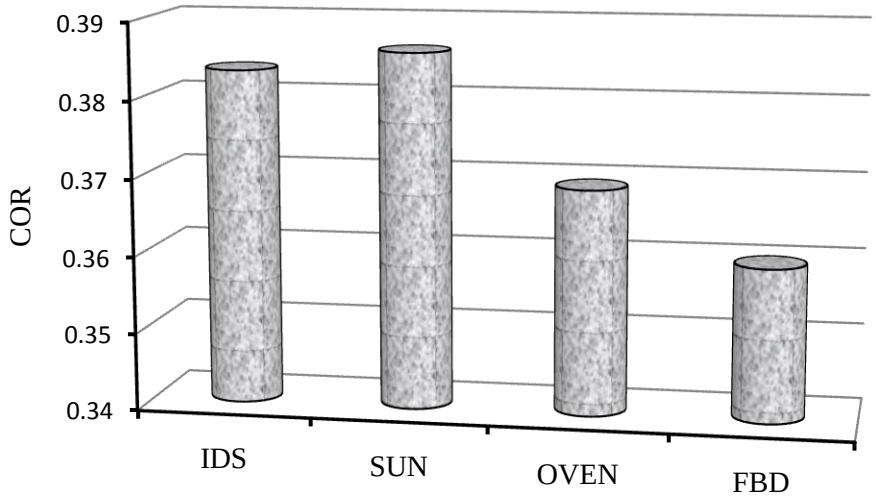

Fig. 5.31 COR Vs Drying method

5.6.1.3 Colour evaluation of dried ginger

Drying affects the colour of biological materials as heat sensitive pigments are affected. Previous studies also reported that hot air drying of aromatic and medicinal plants did not conserve original colour values and caused considerable darkening (Therdthai and Zhou, 2009; Arslan and Ozcan, 2008; Alibas, 2007; Martinov et al., 2007;). Minimum value of ΔE means smallest deviation from its original colour and is an indication of most ideal drying condition. The results of colour evaluation are presented (Table 5.12). The

colour deviation values ΔE, with that of raw were found to differ significantly (Table 5.16) among the methods used for drying. Though value from IDS (34.795) was lowest among the methods other than control, it differed significantly from control. Oven and FBD dried products were more affected as far as colour loss is concerned as evident from the data presented that were 37.479 and 38.131, respectively. The Hue angle was highest for samples from IDS indicating higher location in the first quadrant of the colour wheel while intensity of colour was nearly at par with oven and sun dried samples as indicated by croma values (Fig.5.32). Ginger dried in FBD was affected most as evident from highest ΔE (38.131) and Croma value (25.372) suggesting its unsuitability. Findings are in conformity to similar works carried out by Gowen *et al.* (2008); Ergunes and Tarhan, (2006); Soysal *et al*., (2005) and Sigge *et al.* (2001).

Table 5.12 Effect of drying methods on colour parameters of dried ginger

Method of Drying	L*	a*	b*	ΔE*	Hue	Croma
FBD	65.180	4.860	24.890	38.131	79.005	25.372
OVEN	63.040	6.690	20.560	37.479	71.967	21.587
IDS	66.330	2.443	21.563	34.795	83.535	21.686
SUN	68.480	3.967	19.893	32.214	79.290	20.236

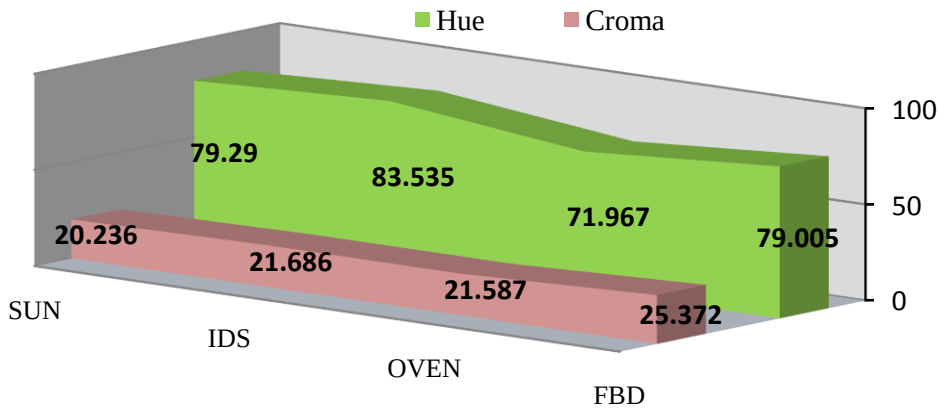

Fig. 5.32 Hue and Croma of dried ginger

5.6.1.4 Oleoresin and volatile oil content of dried ginger

These are the most important quality attributes of ginger and are most heat sensitive. Samples from all the six trays were tested. Oleoresin and volatile oil content in dried ginger from different drying methods are presented in Table 5.13. Highest amount of volatile oil was found in samples from oven drying (0.95%) and lowest (0.40 %) was found in samples from FBD. Volatile oil content of samples obtained from IDS and sun drying (control) were found to be at par. In samples from FBD, significant difference was observed with all other drying methods (Table 5.16) indicating comparatively poor drying condition.

Table5.13. Volatile oil and oleoresin content of dried ginger

Sl. No.	Sample source	Oleoresin, %	Volatile Oil, %
1	IDS	2.60	0.86
2	SUN	2.12	0.80
3	OVEN	2.05	0.95
4	FBD	0.84	0.40

Ginger oleoresin was found to be highest in samples from IDS (2.60%) and affected most in FBD (0.84%). Significant difference was observed in case of samples from IDS with samples from all other drying methods (Table 5.16). Oleoresin content in samples from oven and sun drying were statistically at par. As far as oleoresin content is concerned samples dried in IDS retained maximum percentages.

5.6.2 Turmeric quality studies

5.6.2.1 Texture studies of dried turmeric

Textural properties of dried turmeric from all the four drying methods were studied (Fig. 5.33 to Fig. 5.36). A comparative representation could be seen in Fig. 5.37. It was observed that, turmeric dried in IDS required maximum peak force (8789.006 g) which was an indication of achieving maximum uniform drying whilst positive area under curves was minimum (10745.264 g.sec) amongst all, indicating dried turmeric would require minimum energy during size reduction operations. Significant difference was observed among the values during statistical analysis (Table5.16). Similar findings have been reported by Moreira *et al.* (2008) and Mishra *et al.* (2004).

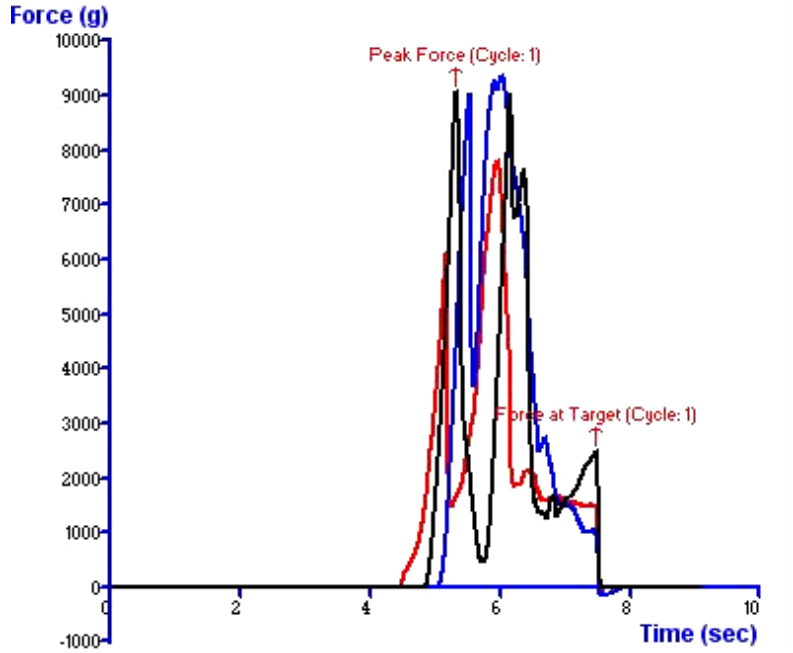

Fig. 5.33 Texture graph of turmeric from IDS

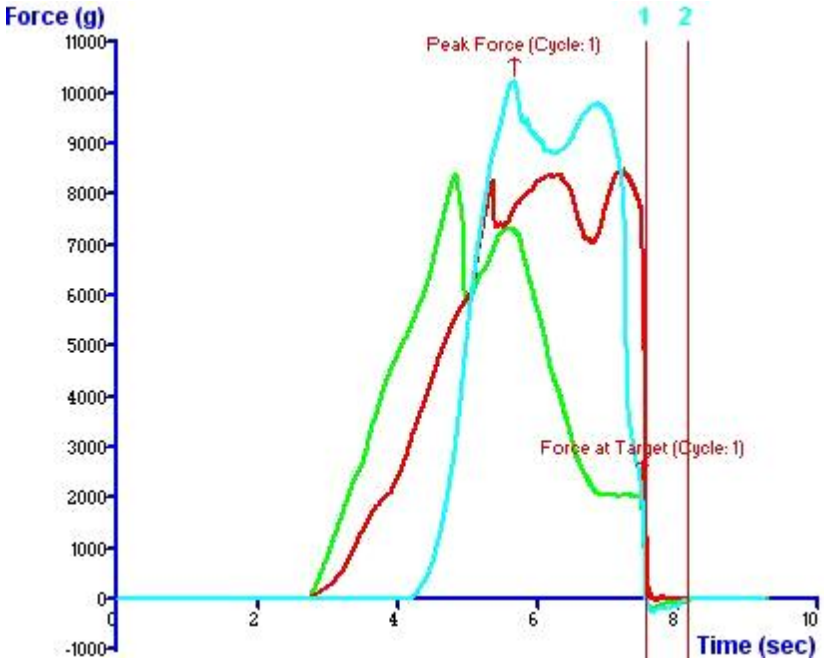

Fig. 5.34 Texture graph of turmeric from FBD

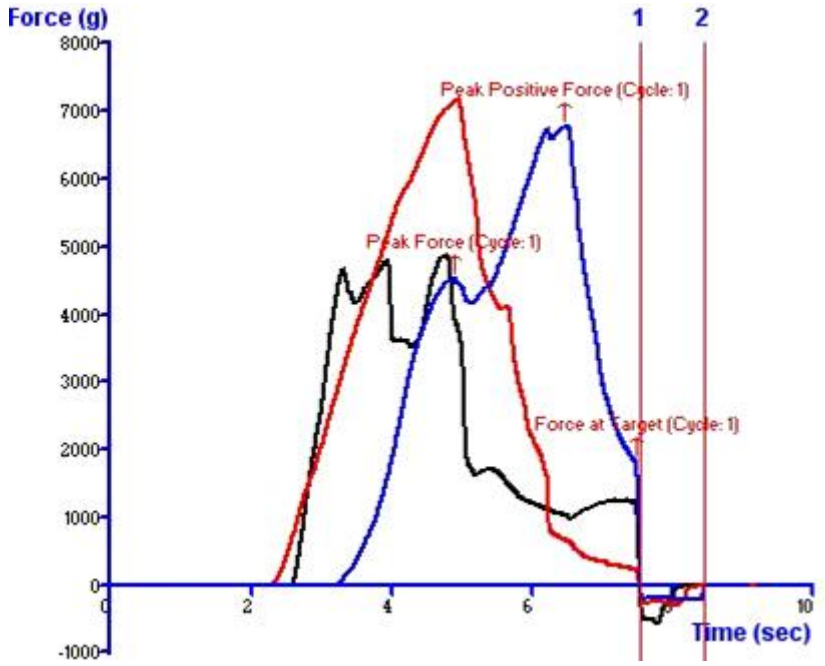

Fig. 5.35 Texture graph of turmeric from Oven

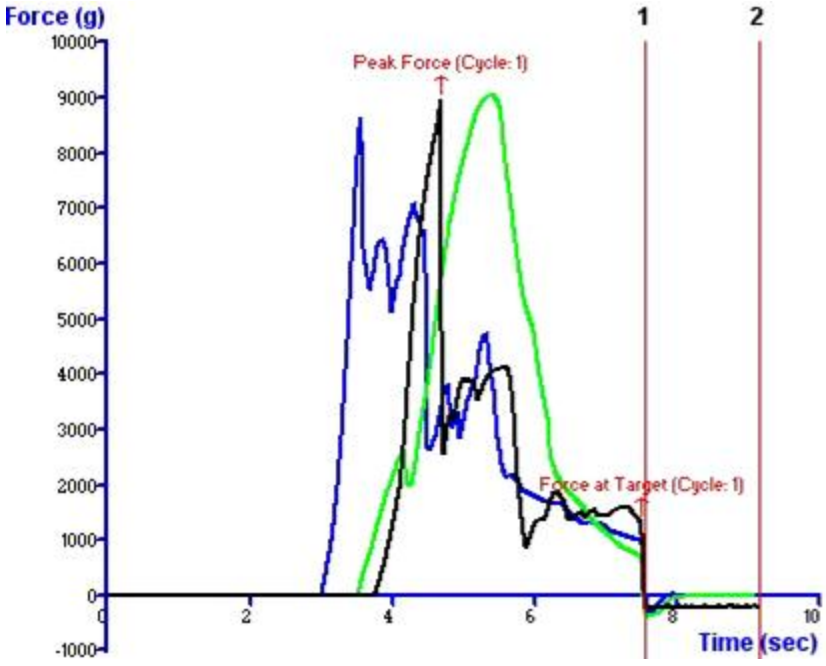

Fig. 5.36 Texture graph of turmeric from Sun drying

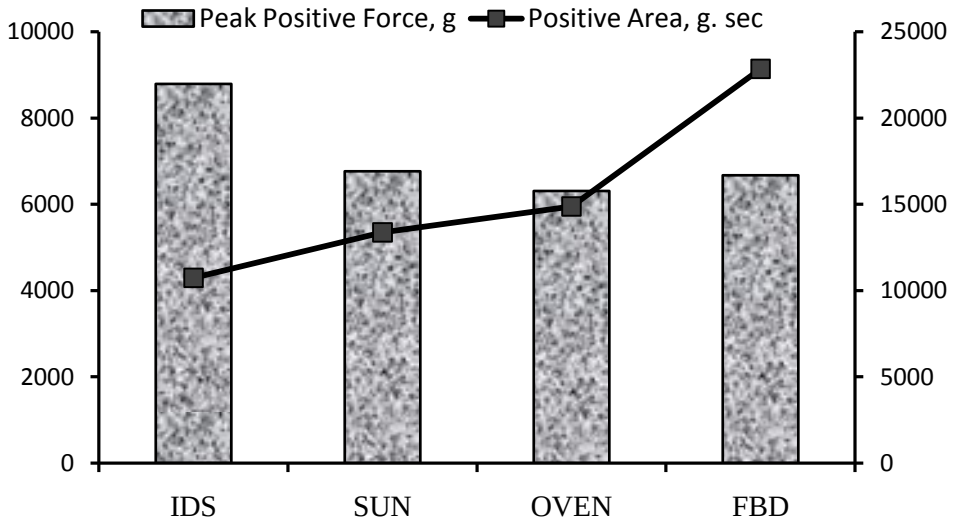

Fig. 5.37 Peak force and positive area: turmeric

5.6.2.2 Colour evaluation of dried turmeric

Quality of turmeric is more dependent on its colour than any other quality attributes. Curcumin, an active ingredient of turmeric is photosensitive and highly responsible for its colour. The results of colour evaluation are presented in Table 5.14. All the colour values differed significantly among themselves for turmeric (Table 5.16). Maximum deviation of colour from control was in case of oven dried (67.354) samples. Lowest value of ΔE (52.681) in case of samples obtained from IDS indicated minimum effect of drying on colour. However, IDS produced samples with minimum Hue angle (64.87^0). Corresponding Croma value being highest (26.786) indicated more intense change in constituents (Fig.5.38). Findings are well supported by similar works reported by Soysal *et al.* (2009); Moreira *et al*.(2008); Gowen *et al*. (2006); Prasad *et al.* (2006) and Moreira *et al*.(2005).

Table 5.14 Effect of drying methods on colour parameters of dried turmeric

Turmeric	L*	a*	b*	ΔE*	Hue	Croma
FBD	35.99	5.28	19.86	61.001	75.11	20.583
OVEN	27.91	3.47	14.69	67.354	76.71	15.086
IDS	47.92	11.38	24.26	52.681	64.87	26.786
SUN	36.93	6.35	10.93	58.213	59.84	12.619

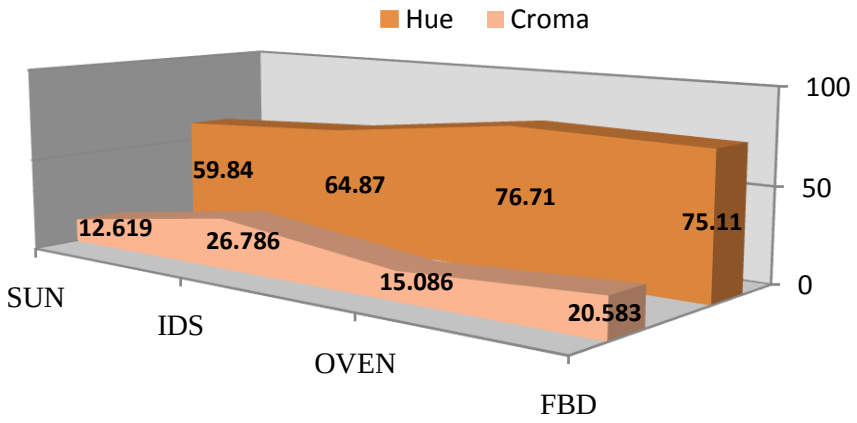

Fig. 5.38 Hue and Croma of dried turmeric

5.6.2.3 Curcumin content of dried turmeric

Curcumin content of turmeric samples obtained from all the four drying methods along with that of raw turmeric were studied following standard procedure (Table 5.15). In order to have a correct comparison, calculations were done on the basis of dry mater weight of each sample. Blanching of washed and cleaned turmeric rhizomes were done prior to subjecting it to drying. Curcumin percentages of raw samples were also determined to know if heat treatment affected curcumin content (Fig.5.39). Taking curcumin content of raw turmeric (6.35%) as base, percent retained in samples after drying was compared for the selected drying methods. It could be seen that, variation in retention of curcumin was only 1.31%, varying between 97.13%and 95.82%. Similar results have been reported by Reema *et al.* (2006); Hossain and Ishimine (2005); Jaypraksasha *et al.* (2002); Chen and Fang (1997). Variation in curcumin content between oven and sun drying was insignificant but significant difference could be seen with samples from FBD and IDS (Table 5.16). Nevertheless, it could be safely said that drying at the present set of conditions, effect on curcumin content was negligible.

Table 5.15 Effect of drying methods on curcumin content

Sample source	S1	S2	S3	S4	S5	Av
RAW	6.583	6.845	5.982	6.548	5.792	6.350
FBD	6.270	6.154	6.175	5.982	6.258	6.168
OVEN	6.140	6.162	6.182	6.081	6.079	6.129
SUN	6.139	6.145	6.074	6.078	6.118	6.111
IDS	6.082	6.098	6.104	6.080	6.072	6.087

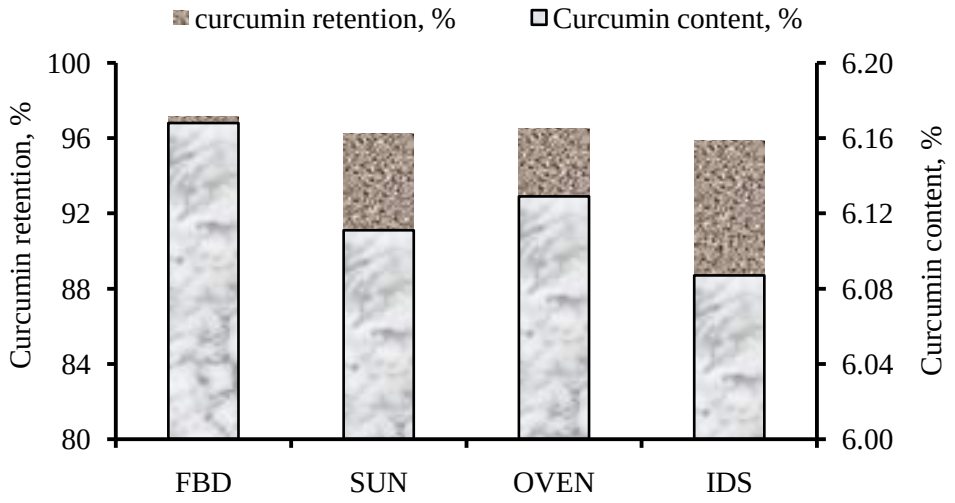

Fig. 5.39 Curcumin content and retention percentages

5.6.3 Statistical analysis of overall quality attributes

Effects of selected drying methods on quality attributes were statistically analyzed to understand critical differences and correlations among the parameters using 1-way analysis of variance (ANOVA). The consolidated results are presented in Table 5.16.

Table 5.16 Statistical analysis of quality parameters

Method	Ginger Colour	Turmeric Colour	Ginger RR	Ginger Vol. Oil, %	Ginger Oleoresin %	Curcu -min, %	Turmeric Texture (g)	Ginger Texture (g)
FBD	38.131	61.001	2.040	0.40	0.84	6.168	6671.828	1343.814
OVEN	37.479	67.354	2.320	0.95	2.05	6.129	6307.689	1340.039
SUN	32.214	58.213	2.160	0.80	2.12	6.111	6764.712	1421.624
IDS	34.795	52.681	2.294	0.86	2.60	6.087	8788.802	1124.597
Sed	0.0265	0.0460	0.036	0.038	0.063	0.024	321.728	74.838
CV	0.9690	0.1718	3.669	11.239	7.388	1.085	10.085	12.799
CD	0.0578	0.1002	0.079	0.083	0.137	0.052	701.367	163.148

Texture values of ginger differ significantly among different drying methods. Even the value obtained for IDS which was smallest, differed significantly from control which happened to be the highest (1421.62 g). In case of turmeric, significant difference was observed among the values. Rehydration ratio of rehydrated ginger samples obtained from

all the four drying methods varried significantly among themselves. The colour deviation values ΔE, with raw ginger was found to differ significantly among the methods used for drying. All the colour values differed significantly among themselves for turmeric as well. In case of ginger volatile oil compound, samples from FBD differed significantly with samples from all other drying methods indicating comparatively poor drying condition in FBD. Significant difference in ginger oleoresin was observed in samples from IDS with samples from all other drying methods. Oleoresin content in samples from oven and sun drying were statistically at par. Variation in curcumin content in dried turmeric between oven and sun drying was insignificant but significant difference could be seen with samples from FBD and IDS.

5.7 Optimization of drying system

The drying processes were optimized for same temperature, using a nine point Hedonic scale. The nine point scale range was fixed based on maximum and minimum values of drying time, specific energy consumption, texture, colour change, rehydration characteristics, oleoresin and volatile oil content in case of ginger which are illustrated in Table 5.17. In case of turmeric, instead of oleoresin; volatile oil and rehydration ratio, curcumin level was considered apart from other parameters (Table 5.18).

Table 5.17 Score for dried ginger among different drying processes for optimization

Drying process	Drying time	Specific Energy consumption	Peak force	Colour change	Rehydration ratio	Oleoresin	Volatile oil	Total
SUN	4	9	1	9	5	6	7	41
IDS	6	3	9	7	7	9	6	47
FBD	9	4	5	1	1	1	1	22
OVEN	1	1	5	2	9	6	9	33

Table 5.18 Score for dried turmeric among different drying processes for optimization

Drying process	Drying time	Specific Energy consumption	Peak force	Colour change	Curcurmin content	Total
SUN	1	9	9	6	4	29
IDS	6	4	2	9	9	30
FBD	9	3	4	4	3	23
OVEN	1	1	1	1	1	5

In case of ginger (Table 5.17), the panel of researches gave highest average score (47) to IDS and FBD scored lowest (22). The FBD system is totally unsuitable for ginger drying as evident from its lowest score. Average score in case turmeric for IDS and sun drying was almost at per which were 30 and 29, respectively. Oven drying scored very low score (5) suggesting its absolute unsuitability for turmeric drying. Similar findings have been reported by Lasekan *et al.* (2012); Kaleemullah and Kailappan (2005); Ahmed and Shivhare (2001).

5.8 Energy balance and utilization efficiency

Energy utilization efficiency study was carried out for bio-waste fired assembly and compound parabolic solar collector separately.

5.8.1 Energy supplied to the combustion chamber

Mass of fuel (rice husk) supplied, m_f = 26 kg

Calorific value of rice husk, CV = 3000 kcal/kg

Energy supplied to the furnace, $m_f \times CV$ = 78000 kcal = 326352 kJ

Duration of running the furnace = 31 h

Rate of energy supplied to the furnace = 326352/(31×60×60) kW

= 2.92 kW

5.8.2 Energy available in plenum chamber from combustion side

$$Q_c = m_c \, Cp \, \Delta T_c \qquad \text{----------(5.1)}$$

m_c = rate of mass flow = ρ A v

C_p = specific heat of air at constant pressure = 1.0005 kJ/kg.^{0}K

$\Delta T_c = T_h - T_{ambient}$ = 343-303 = 40^0 K

ρ = Density of air at 60°C = 1.0335 kg.m^{-3}

A = Area of cross section through which ambient air was passed

= 2(0.23×0.16) = 0.0736 m^2 [∵ No. of cross section=2]

Air velocity, v = 0.6 m.s^{-1}

So, m_c = 0.0456 kg.s^{-1}

Therefore, Q_c = 1.82 kW

Therefore, efficiency of the bio-waste fired assembly

$$\eta_c = \frac{\text{Heat available in plenum chamber from combustion side}}{\text{Heat supplied to the furnace}} \times 100$$

= 62.32 %

5.8.3 Energy available to the compound parabolic solar collector

5.8.3.1 Incident energy

$$Q_i = I_\alpha \times A_{collector} \quad \text{----------(5.2)}$$

= 456.601 W.m^{-2}×3.73 m^2 [∴ Av. Solar intensity $I_\alpha$was 456.601 W.m^{-2}]

= 1.689 kW

5.8.3.2 Energy available in collector surface area

Overall Heat Transfer Co-efficient of Solar Collector:

Emissivity of glass cover, ε_{cover} = 0.88

Emissivity of absorber, $\varepsilon_{absorber}$= 0.95

Slope of solar collector with horizontal = 15°

Gap between the absorber and cover, d = 5cm

Absolute temperature of air, T_{air} = 30+273 = 303 ^{0}K

Temperature of absorber, T_{abs}= 56+273 = 329 ^{0}K

Temperature of glass cover, T_c = 38+273 = 311 ^{0}K

Heat transfer co-efficient of air/wind, $h_{wind/air}$ = 7 W/m^2 ^{0}K

Stefen Boltzmann constant, σ = 5.67×10^{-8} W m^{-2} K^{-4}

For radiation to the sky from glass cover,

$$h_{r,c-a} = \varepsilon_c \sigma (T_{cover}^2 + T_{air}^2)(T_{cover} + T_{air}) \quad \text{------ (5.3)}$$

$$= 5.775 \text{ W/m^2 K}$$

For radiation from absorber plate to cover,

$$h_{r,p-c} = \frac{\sigma (T_{absorber}^2 + T_c^2)(T_{absorber} + T_c)}{\frac{1}{\varepsilon_{absorber}} + \frac{1}{\varepsilon_{cover}} - 1} \quad \text{------- (5.4)}$$

$= 6.255\ \mathrm{W/m^2\ K}$

Rayleigh Number:

$$R_a = \frac{g\beta \Delta T L^3}{v\alpha} \qquad \text{----------(5.5)}$$

where, g = acceleration due to gravity = 9.81 ms^{-2}

β = Thermal expansion coefficient = 1/T = 3.125×10^{-3}, T = (38+56)/2+273

ΔT = 56-38 = 18 ^{0}K

L = 0.05m = 5 cm

v = kinematic viscosity of air at 32^0K = 15.68×10^{-6} m^2s^{-1}

α = thermal diffusivity of air at 32^0K = 22.07×10^{-6} m^2s^{-1}

Therefore, $\mathbf{R_a = 19.4\times10^4}$

Nusselt Number (Hollands *et al.*, 1976)

$$Nu = 1 + 1.44\left[1 - \frac{1708}{R_a cos\Theta}\right]\left[1 - \frac{(sin 1.8\Theta)^{1.6}\times 1708}{R_a cos\Theta}\right] + \left[\frac{(R_a cos\Theta)^{\frac{1}{3}}}{(5830)^{\frac{1}{3}}} - 1\right] \text{---------- (5.6)}$$

Here slope, $\Theta = 15°$

Hence, **Nu = 4.6**

Convective heat transfer co-efficient from plate to cover,

$$h_{p-c} = Nu\frac{k}{L} \qquad \text{---------- (5.7)}$$

$= 2.6\ \mathrm{W/m^2{}^0K}$

(Thermal conductivity of air, k = 0.02816 W/m ^{0}K)

So, the top heat loss co-efficient,

$$U_t = \left[\frac{1}{h_{p-c}+h_{r,\ p-c}} + \frac{1}{h_{r,\ c-a}+h_{\frac{wind}{air}}}\right]^{-1} \qquad \text{---------- (5.8)}$$

$= 5.28\ \mathrm{W/m^2{}^0K}$

Considering negligible edge and bottom loss due to insulation, (i.e. U_e and U_b = 0)

Overall heat loss co-efficient

$$\mathbf{U_L = (U_t + U_e + U_b) = 5.28\ W/m^{20}K}$$

Therefore rate of heat loss,

$$Q_o = U_L A(T_{abs} - T_{air}) \quad \text{---------- (5.9)}$$

$$= 511.999\ W$$

Amount of solar radiation received by the collector

$$Q_i = IA \quad \text{---------- (5.10)}$$

$$Q_i = 1689.42\ W$$

Thus, the rate of useful energy extracted by the collector,

$$\boldsymbol{Q_u = Q_i - Q_o = 1177.438\ W}$$

5.8.4 Heat available in the plenum chamber from solar side

Temperature at inlet of the solar collector,

$T_i = T_{ambient}$

$= 30+273 = 303^0K$

Temperature at outlet of the solar collector,

$T_o = 46+273 = 323^0K$

Hence, $\Delta T_s = T_o - T_i = 20^0K$

Heat carried away by the air from the solar collector at a velocity of 0.2 m/s (measured) is given by,

$$Q_{actual} = mC_p(T_{outlet} - T_{inlet}) \quad \text{---------- (5.11)}$$

where, [area = 0.23 m^2 and

humid volume (at 46^0 C and 80% humidity) = 0.885 m^3/kg]

$$\text{m} = \text{mass flow rate} = \frac{\text{Cross sectional area of collector} \times \text{Velocity of air}}{\text{Humid volume of air at 46 ℃ 80\% RH}}$$

$= 0.0519$ kg/s

C_p = 1.0005 kJ/kg ^{0}K

Therefore, $\boldsymbol{Q_{actual}} = 832.416\ W$

Collector heat removal factor,

$$F_r = \frac{Q_{actual}}{Q_u} = 0.70$$

The instantaneous thermal efficiency of the collector:

$$\eta = \frac{Q_{actual}}{AI} \times 100 = \mathbf{49.27}\%$$

5.8.5 Total heat available in the plenum chamber

$Q_{Total} = Q_c + Q_s$ [where, Q_s= Solar Q_{actual}]

= 1.82+0.832= 2.656 kW

5.8.6 Heat utilized in the drying chamber

By solar power,

Latent heat of evaporation of water at 46°C, h_{fg} = 2392.4 kJ.kg^{-1}

Amount of moisture removed = 3.2 kg

Therefore, amount of heat utilized = 7655.68 kJ

Or, rate of heat utilized for 8 hours

= 7655.68 ÷(8×60×60) = 265.822 W ----------(A)

By Biomass power,

Latent heat of evaporation of water at 55°C, h_{fg} = 2373.1 kJ.kg^{-1}

Amount of moisture removed = 24.4 kg

Therefore, amount of heat utilized = 57903.64 kJ

Or, rate of heat utilized

= 57903.64÷(23×60×60) = 699.319 W ----------(B)

Total heat utilized from both power source, (A)+(B) = 965.141 W

5.8.7 Overall energy efficiency of the drying system

$$\eta_o = \frac{\text{Energy utilized in the drying chamber}}{\text{Total energy supplied to dryer}} \times 100$$

= 36.33%

5.9 Experimental photographs

Different stages of ginger and turmeric during drying experiments in IDS are presented in Fig. 5.40 and Fig. 5.41.

Fig. 5.40 Different stages of ginger drying experiment

Fig. 5.41 Different stages of turmeric drying experiments