The hybrid drying of pistachios by solar energy and high electric field

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Abstract: An innovative access to sun drying was tested in this study using a flat bed as product support and high electric field exciter. The moist unshelled pistachios were dried in electric fields under open sun and variation of weight was recorded. The results showed that the Logarithmic model was found to be the most suitable for describing drying curve of pistachios. By applying 10, 20 and 30 kV electric fields about 0.58 to 3.1 W for each kilograms moist pistachio in solar drying; the nuts moisture could be cut in 8 h to a proper level. The energy-efficient and lower cost of the drying apparatus with a simple needle and plate assembly are the advantages of this technique.

Keywords: sun drying, high electric field, pistachios

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1 Introduction

Since many years ago, Iran has had superiority in pistachio cultivation. Pistachio is one of the most important agricultural products of non-petroleum exportations. Although Iran is the biggest exporter around of the world because of 40% production of the world's pistachio and having 60.7% of the whole world's market (Amiriaghdaie, 2009), but still could not compete with its powerful rivals who have advanced technologies in producing, packaging and exporting.

Pistachio nuts are cultivated in grape-like cluster with an external skin, called the hull that encases each nut, when ripen the hull turns rosy and the inside shell splits, signifying the nut is ready to be harvested (Kouchakzadeh, 2013). Iranian pistachios are mechanically shaken from the tree or by hand, fall directly onto a catching frame, and loaded on trucks to send to the processing plant where the workers use machines to remove the hull and dry the nut within 12–24 h after harvest. The pistachios moisture at harvesting time is about 40%–50% (dry basis (d.b.)) according to date and climatic location. But, for storage pistachios need to dry 5%–7%. Drying pistachios in free air cannot be done as quickly as needed to prevent conditions like fungal metabolites showing toxin growth (Kouchakzadeh, 2011). So, pistachios expose hot air at temperatures 50℃–93℃ for 3–8 h in flat plate continues dryers such as Figure 1. For 25 t load of pistachios these dryers consume about 3500 MJ energy that is supplied by gas torches (Hoseinzadeh, 2015; Kouchakzadeh and Tavakoli, 2011). The drying process is based on empirical method, with very little use of scientific principles. In the last years, several drying techniques and methods of pistachios have been developed, such as the introduction of ultrasounds (Kouchakzadeh, 2013), the use of vacuum dryer (Kouchakzadeh and Haghighi, 2011), microwave dryer (Kouchakzadeh and Shafeei, 2010) and agitated dryer (Kouchakzadeh, 2014). However, the used method, drying is still considered to be an expensive process due to the total amount of consumed energy in relation with empirical dryer designs.

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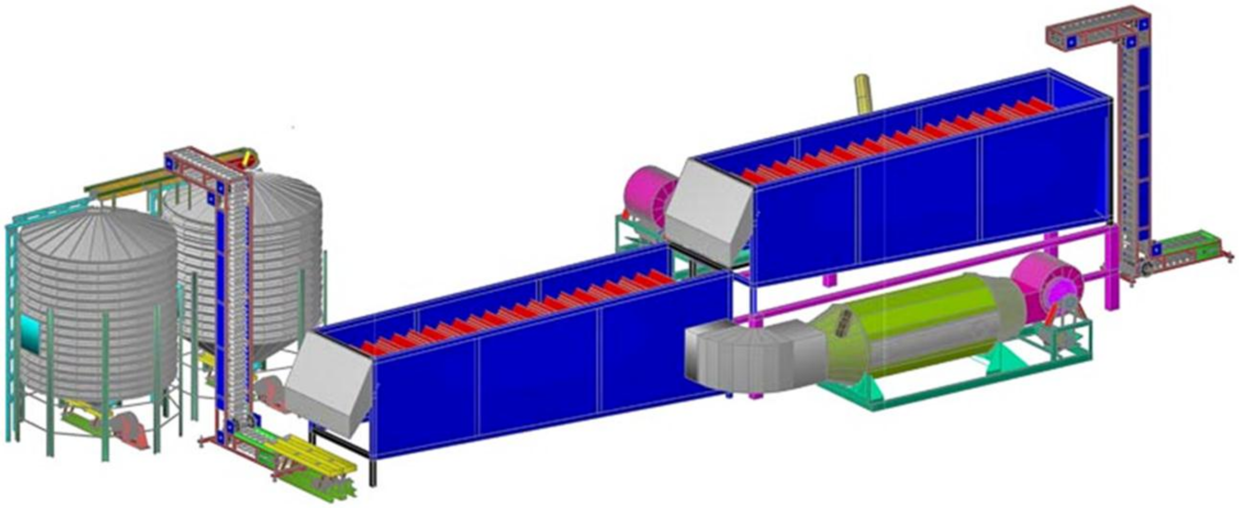

Figure 1 Illustration of pistachio flat plate continuous dryer (CMD 8000, Momtazan Ind. Co. Iran)

The pistachio drying process could be conducted by using solar energy. Pistachio products are dried on paved ground under the sun or with a drying system. In natural sun drying method dehydration pistachios need 2-3 days period that can produce conditions in with Aflatoxin growth. The pistachio drying process is affected to several factors of the crop, to the ambient conditions and to the harvest treatments (Cao et al., 2004). Despite many defects, solar drying of pistachios is tried in many places in Iran because it is abundant and free.

The combination of solar drying with other dehydration method may be resolved these imperfections. Among emergent new technologies, high electric field (HEF) dehydration is encouraging because of low energy consumption and high product quality (Rouaud and Havet, 2009). In HEF-drying, high electric field intensity is enforced to generate ionized forms of air-constituents in the foodstuff. The ionized air is a bunch of molecules bound simultaneously by the Coulomb force connected with an overabundance or lack of electrons (corona discharge, Figure 2). The movement of the air ions in a strong electric field produces an ionic wind. Loss of water vapor occurs as the water molecules direct themselves towards an electric field. When a decreasing of entropy occurs, this down the temperature of the material being dried. The thermodynamic causes mixed up in the drop in temperature that transpires under HEF comprise the quick rate of evaporation and the emitting heat interaction of electric fields with dielectric stuffs (Bajgai et al., 2006).

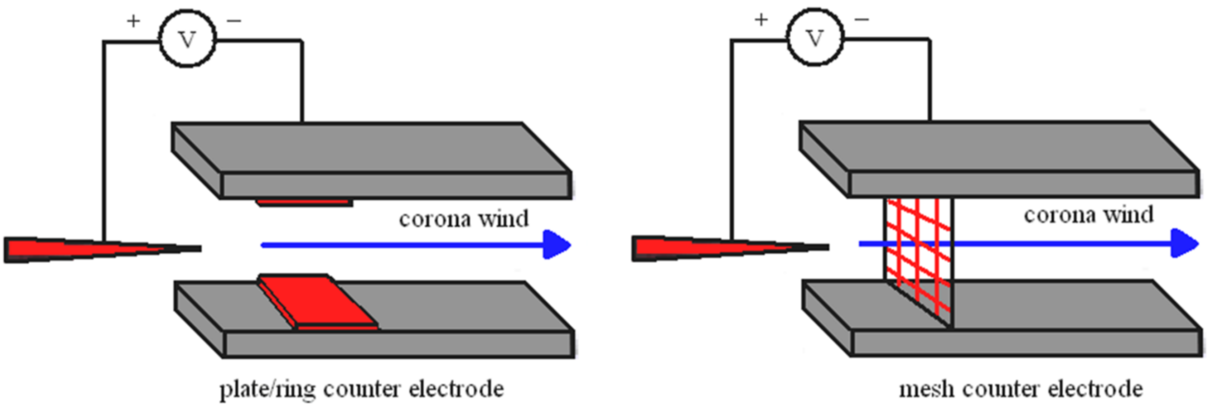

Figure 2 Scheme of a corona discharge (plate/ring and mesh configuration)

The effects of high electric fields on biological stuffs were considered to improve mass transfer for different products and processes. Bajgai and Hashinaga (2001) used an alternating current high-voltage electric field to dry spinach. Chen and Barthakur (1991) studied the effect of a corona discharge electrode system on the drying characteristics of potato slabs with different thicknesses. Cao et al. (2004) studied the effect of electric field on the drying characteristics of wheat. They also studied the effect of a high-voltage electric field on the drying rate of rough rice (Cao et al., 2004).

The combination of high electric field during solar drying of foodstuffs has not yet been tried. The present work-study is the effect of high electric field in open sun heating with natural convection method on pistachios drying kinetics using the mathematical approach. Mathematical modeling can help in providing the optimum parameters that should be applied to optimize the operating conditions.

2 Materials and methods

This study was down in a pistachio processing plant in Qom province central Iran. In this region, harvest commonly starts in late August and continues for 4–6 weeks. The pistachio nuts were daily harvested to match the capacity of the post-harvest processing units. After dehulling, washing and separation the nuts were sent to drying.

A monolayer of moist unshelled pistachios were scattered in the horizontal square 1×1 m^2 stainless steel flat bed under open sun. As illustrated in Figure 3, the bed was equipped with load sensor (SM601, Sewha, Inc., Korea). The load sensor was placed at the middle of the plate that contacts the ground surface with the basis. A 20 mm thick layer laminated plastic electrically insulated the stainless steel plate bed. A 1×1 m^2 copper screen (50×50 mm mesh) was placed on the upper edge of the insulator plate. A copper electrode needle with 25 mm height and 3 mm diameter has been welded before to each mesh knot, as the sharp points of electrodes were about 3-5 mm from above the pistachios surface. A 30kV/50mA DC power supply (Poyamobadel, Co, Iran) was used as voltage source. The LED display shows the output current and voltage at anytime.

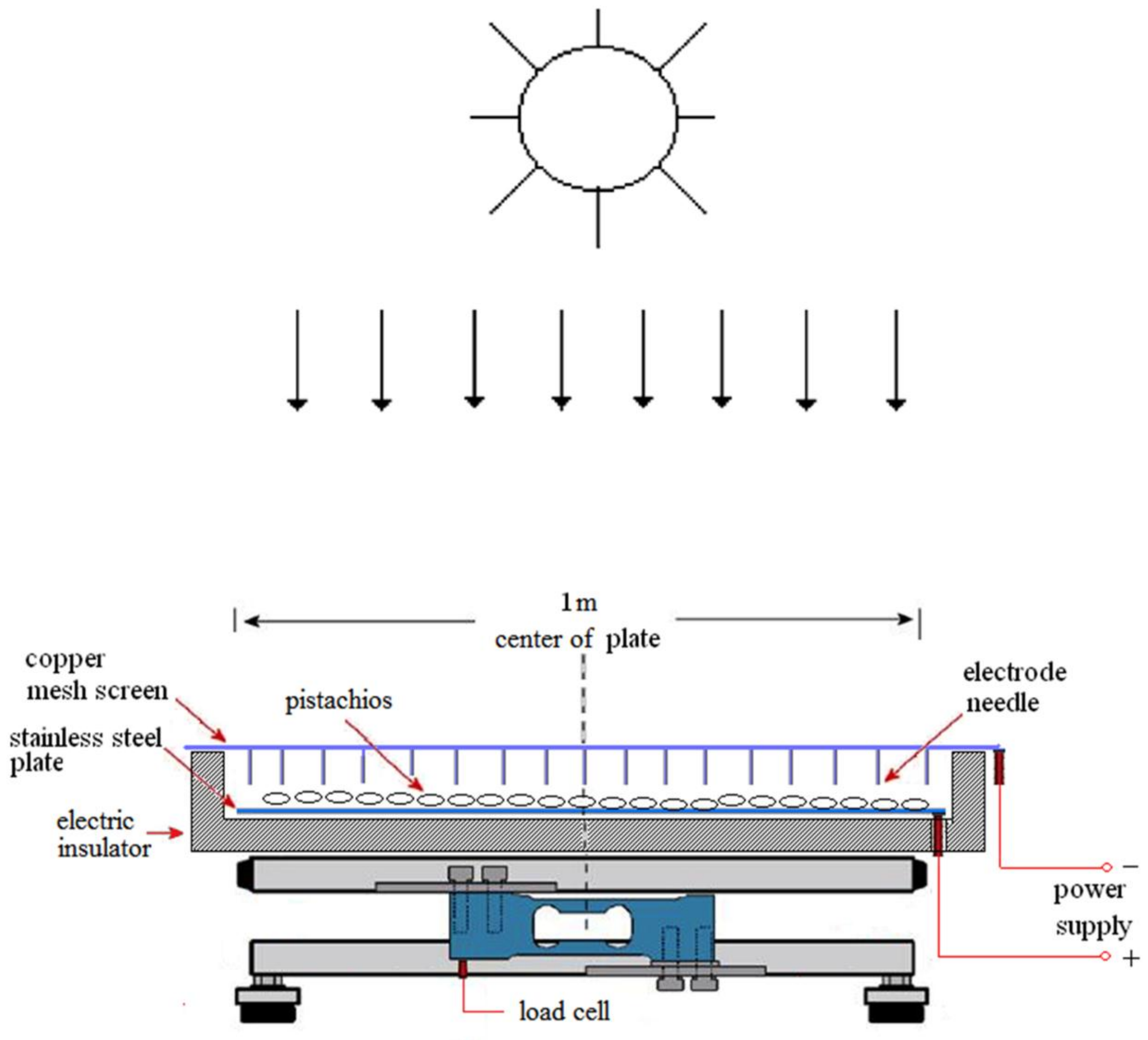

Figure 3 schematic of tests apparatus

To measure the solar radiation flux that is incident on a plane surface in W/m^2 from a 180° field of view, a pyranometer (LP02-LI19 hukseflux, Netherlands) was used. The relative humidity and temperature of the surrounding air were checked with the aid of a Hand-held thermo-hygrometer (LUTRON, HT-3015, Taiwan) and wind speed was measured continuously by anemometer (LUTRON, AM-4201, Taiwan) at 1 m above the surface of the drying bed. The initial moisture content of samples was determined by oven drying at temperature of 130 ℃ for 6 h according to a standard method (ASABE, 2005). About 150 g of pistachios was placed in an oven, its final weight was taken, and the difference in weight was taken as water loss and expressed as grams water for each gram dry matter. Then monolayer of pistachios was lain on drying chamber of device dryer and variation of weight of pistachio with the resolution of 10 g recorded continually. The signals from load cell are recorded by a high speed data acquisition system (TML DC-204R) that is a compact recorder equipped with signal conditioners and sensor input conversion cable (CR-6180) that used for connecting transducers.

2.1 The tests

About 7 kg of moist unshelled pistachios with the initial moisture content between 50%-60% (db) were scattered in mono layer in device dryer under open sun, then the variation of weight of pistachio recorded and moisture content were determined on anytime. Test experiments were carried out with 0, 10, 20 and 30kV DC electric potential between stainless steel plate and copper mash screen. Experiments were performed in triplicate in 12 days. Drying with 0 kV was down in day 1 and repeated in day 5 and day 9, drying with 10 kV was performed in day 2 and down again in day 6 and day 10, separately for 20 kV and 30 kV in day 3, day 7, day 11, day 4, day 8 and day 12, respectively. Al tests were started at 8 am and continued at 4 pm). The averages of 12 days hourly solar radiation intensity and ambient air-temperature are shown in Figure 4; the plots of wind speed and air relative humidity during experiments were presented in Figure 5.

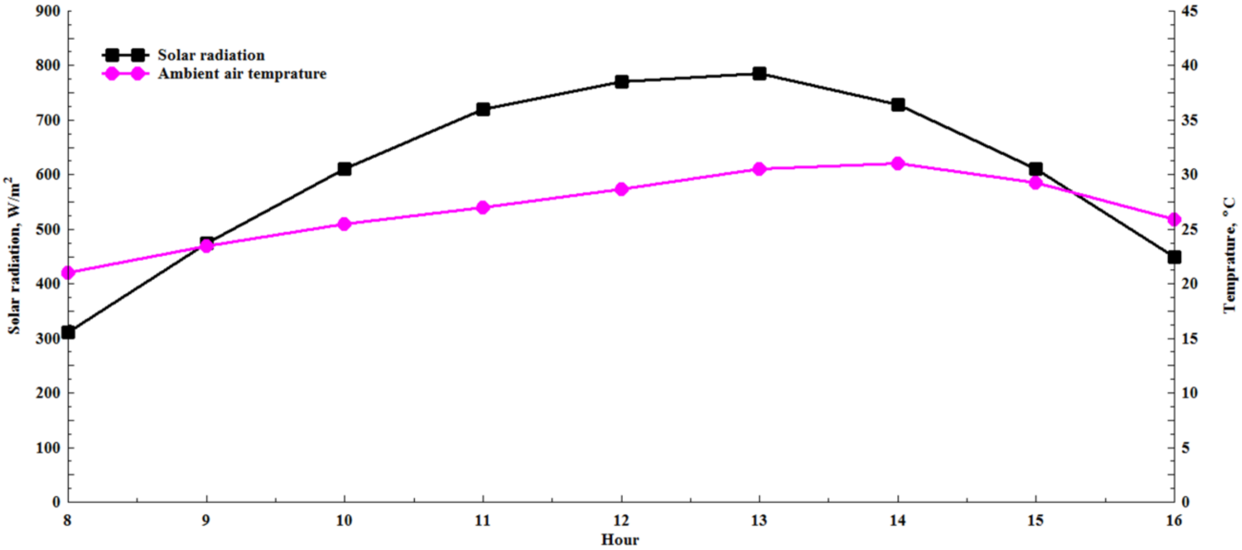

Figure 4 Hourly solar radiation intensity and ambient air temperature (averages of 12 days)

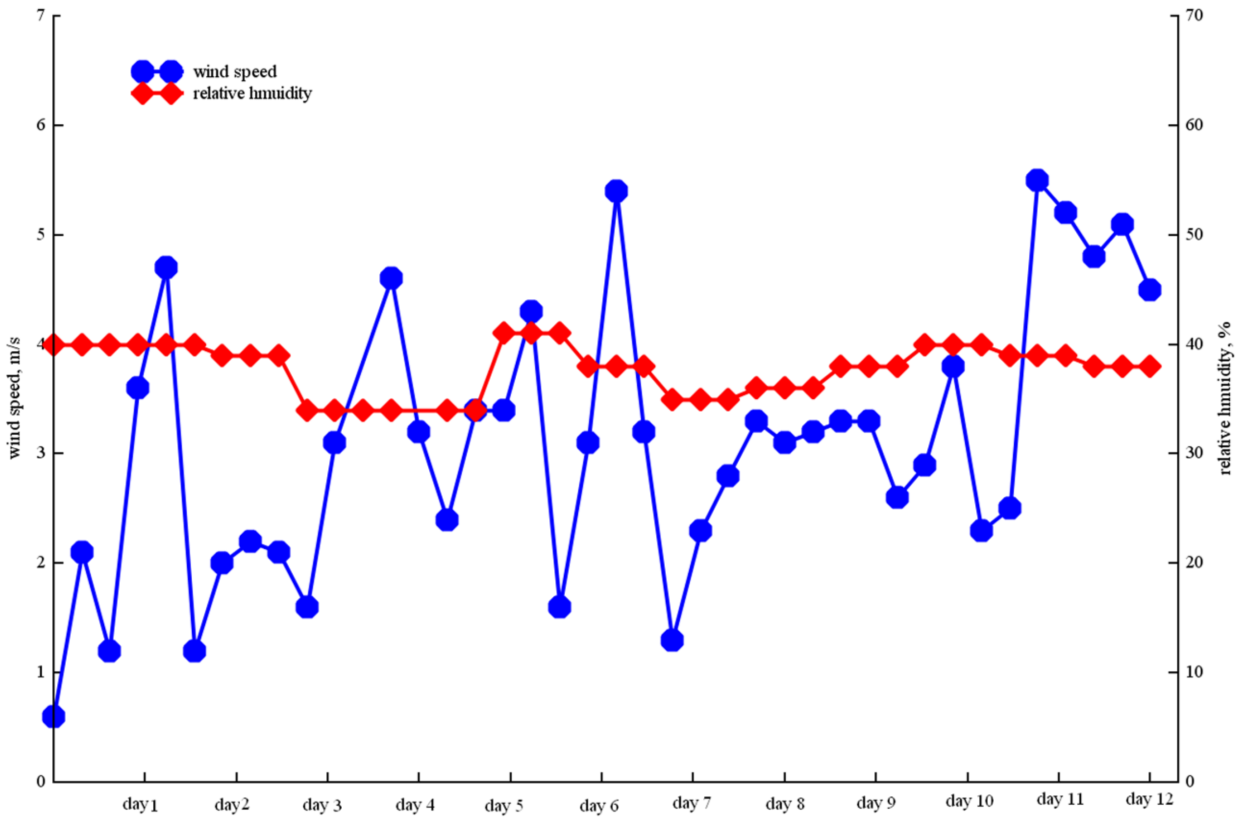

Figure 5 Plots of wind speed and air relative humidity during 12-day experiments

2.2 Mathematical modeling

The moisture ratio (M_R) was calculated by dividing present moisture by its initial moisture. Moisture ratio curves were adapted with Newton, Page, Henderson Pabis, Logarithmic and Wang and Sing models that were tested by some researchers such as: Midilli and Kucuk (2003), Kashaninejad et al. (2007) and Kouchakzadeh and Shafeei (2010), Kouchakzadeh and Haghighi (2011) for drying kinetic of pistachios. Table 1 shows the models.

Table 1 mathematical models applied to drying curves

	Models	Name
1	$M_R = \exp(-kt)$	Newton
2	$M_R = \exp(-kt^n)$	Page
3	$M_R = a\exp(-kt)$	Henderson Pabis
4	$M_R = a\exp(-kt)+c$	Logarithmic
5	$M_R = 1+at+bt^2$	Wang and Sing

The acceptability of models was determined by the coefficient of determination R^2, and the reduced value of mean square of deviation χ^2. The reduced chi-square can be calculated as Equation (1) (Mohamed et al., 2008):

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

Where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is predicted moisture ratio, N is number of observation, and n is number of constants. Non-linear regression analyses were down by using statistical computer program.

2.4 Drying efficiency

The cumulative drying efficiency values were calculated as the averaged energy consumption for water evaporation divided by the supplied power and time (Mousa and Farid, 2002), see Equation (2):

$$n_d = \frac{m_w \lambda_w}{P\Delta t_{on}} \times 100 \qquad (2)$$

Where: n_d is the drying efficiency in percentage; m_w is the mass of evaporated water in kg; λ_w is latent heat of vaporization in J/kg; P is the power in W and Δt_{on} is the time interval in s, latent heat of vaporization at the evaporating temperature (100 $^\circ C$) was taken as 2257 kJ/kg (Kavak Akpinar, 2010).

The value of P was supposed as Equation (3):

$$P = (GSR \times A) + (I \times V) \qquad (3)$$

Where: GSR is the global solar radiation in W/m^2, A is the surface area of dryer in m^{-2}, I is the current of DC circuit in A and V is the electric potential in V.

3 Results and discussion

The experiential data were presented as a plot of M_R vs. time as shown in Figure 6. From slope of the curves, drying rate under open sun and 0 kV has a liner steady slope but after applying 10, 20 and 30 kV electric potential the drying rates have more than one falling rate period. This may be caused by capillary property and cell structure of the pistachio nut as showed by the rate of drying, which was not constant (Kouchakzadeh, 2011). During the first period, the surface of product behaves as a surface of free water. The rate of moisture content removal from the surface is dependent on condition of places that drying is occurred, but in second stage the moisture migration from the inter layers of products to surface, this stage is dependent on the rate of diffusion of moisture from n the product to the surface and also moisture removal from the surface. Both the external factors and internal mechanism controlling the drying process in two main rate regimes are important in determining the drying rate of products (Kouchakzadeh and Tavakoli, 2011). Desiccation under open sun without electric potential should be classified in first stage of drying because after 8 h the moisture ratio could not be received to 0.7. But, the combined solar and electric field should be arranged in multi stage the moisture migration.

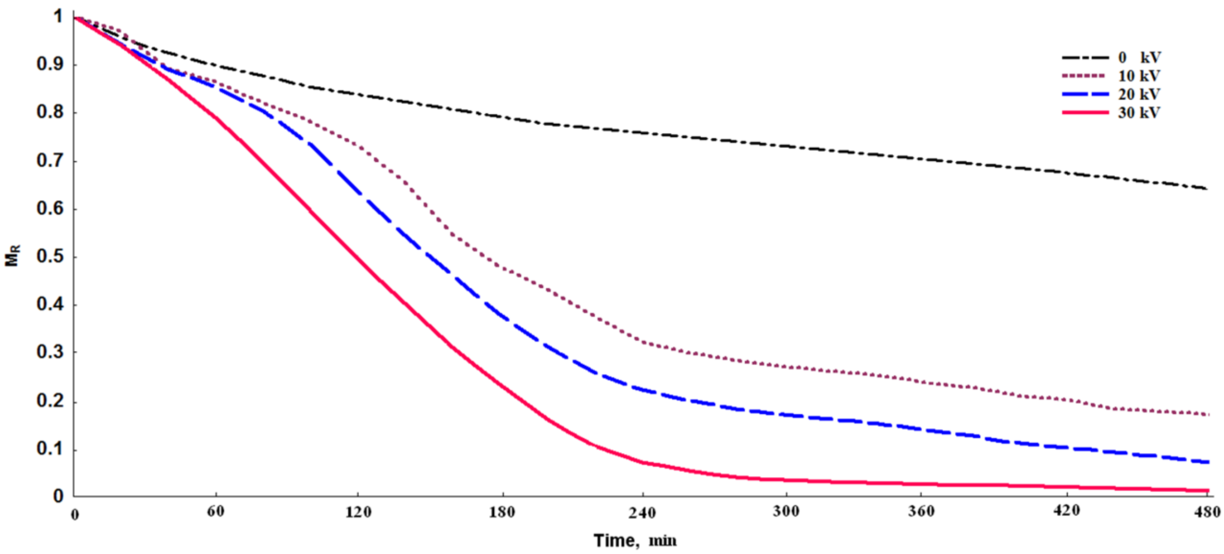

Figure 6 Variation of pistachio's moisture ratio vs. time

According to highest R^2 and lowest χ^2, as shown in Table 2 the best fitted model for both solar drying (no electric potential) and combined solar and high electric field during time interval are Logarithmic model. But, with applying high electric field in solar drying, the models were not converted to new formats and the constant factors of term were replaced only. In previously study of pistachios solar drying by Kouchakzadeh, the Logarithmic model was selected to represent the drying behavior of pistachios under open sun (Kouchakzadeh, 2013), also Midilli and Kucuk (2003) reported comparable Logarithmic model results for prediction of behavior of thin layer drying of pistachio by using solar energy.

Table 2 Modeling of moisture ratio vs. drying time in various electric potential

Electric potential (kV)		0	10	20	30
Newton model	k	0.0344	0.5413	0.0652	0.0894
	R^2	0.9330	0.9230	0.9267	0.9390
	χ^2	3.15×10^{-6}	4.97×10^{-7}	2.23×10^{-7}	3.95×10^{-6}
Page model	k	0.0587	-0.0164	0.0383	0.0587
	n	0.8486	2.0260	1.4539	0.8486
	R^2	0.9690	0.9685	0.9590	0.9733
	χ^2	4.33×10^{-7}	1.69×10^{-7}	6.24×10^{-6}	1.30×10^{-6}
Henderson Pabis model	a	0.0167	0.5949	0.9049	0.9437
	k	0.0734	0.1805	0.0510	0.0734
	R^2	0.9530	0.9313	0.9520	0.9511
	χ^2	3.40×10^{-7}	5.69×10^{-6}	1.59×10^{-6}	5.11×10^{-7}
Logarithmic model	a	1.4272	0.8503	0.2825	1.1422
	k	-0.4160	0.9199	0.3019	0.3160
	c	0.5126	0.9118	0.7238	-0.0126
	R^2	0.9885	0.9790	0.9779	0.9877
	χ^2	6.26×10^{-6}	1.22×10^{-6}	6.39×10^{-7}	3.23×10^{-6}
Wang and sing model	a	0.5160	-0.3976	-0.0927	0.6460
	b	0.6534	0.0086	0.0106	0.0654
	R^2	0.1860	0.9470	0.9480	0.9360
	χ^2	4.37×10^{-7}	2.32×10^{-7}	3.93×10^{-6}	4.30×10^{-7}

Some parameters during drying of pistachios are presented in Table 3, as shown in Table 3, the average drying efficiencies from 24.5% in 0 kV raised to 27.1%, 43% and 51.2% in 10 kV, 20 kV and 30 kV, respectively.

Table 3 Some parameters during drying of pistachios

Experiment day	1	2	3	4	5	6	7	8	9	10	11	12
Initial mass (kg)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Final mass (kg)	6.3	6.1	5.6	5	6.4	6.2	5.2	4.9	6.2	5.6	5.3	5
Evaporated water (kg)	1.2	1.4	1.9	2.5	1.1	1.3	2.3	2.6	1.3	1.9	2.2	2.5
Time interval (h)	8	8	8	8	8	8	8	8	8	8	8	8
Electric potential (kV)	0	10	20	30	0	10	20	30	0	10	20	30
Electric current (μA)	0	472	578	776	0	460	602	742	0	432	580	700
Electric energy (W)	0.00	4.72	11.56	23.28	0.00	4.6	12.04	22.26	0.00	4.32	11.6	21
Electric energy per unit mass of moist pistachios (W/kg)	0.00	0.63	1.54	3.10	0.00	0.61	1.61	2.97	0.00	0.58	1.55	2.80
Solar energy in time interval (W)	3844	3817	3874	3886	3810	3880	3889	3832	3868	3882	3862	3842
Total energy (W)	3844	3822	3886	3909	3810	3885	3901	3854	3868	3886	3874	3863
Drying efficiency (%)	24.5	28.7	38.3	50.1	22.6	26.2	46.2	52.9	26.3	38.3	44.5	50.7

The extent of corona wind under high electric field drying is small. Although the voltage applied remains high, the small current cuts the consumption of electrical energy to justly low levels during the drying process. As shown in Table 3, the maximum 3.1 W per unit weight of wet pistachios in 30 kV has been consumed that has done this an energy-efficient method. The electrical power used in high electric field drying is small compared to oven and hot air drying. The lower cost of the drying apparatus with a simple needle and plate assembly, the convenience of its use with combination of other methods is attributes of this technique.

The moisture diffusion rate of interior pistachios kernels rose with the high electric field and the influence of the corona wind under higher voltage were stronger. But, it seems the surface color of nuts under 30kV would become browner than 20 kV, 10 kV and 0 kV, respectively. Color is an important attribute of dried fruit and edible nuts. Deterioration of color in dried fruits also shows loss of nutritious.

4 Conclusions

In this study, forced drying of pistachios under open sun by applying high electric field was probed. No continuous falling rate cycle of drying was observed. The results showed that the Logarithmic model was found to be the most fitting for describing drying curve of pistachios. According to data presented in Table 2, the average drying efficiencies rise from 24.5% to 27.1%, 43% and 51.2% in 0, 10, 20 and 30 kV, respectively. One of the inherent disadvantages of natural sun drying method of pistachios has slow rates that may produce conditions in with Aflatoxin growth. We estimate by applying 10, 20 and 30 kV electric field about 0.58 to 3.1 Watt for each kilograms moist pistachio in solar drying, the nuts moisture could be cut in 8 h to a proper level.

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