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ORIGINAL PAPER

Effect of Pre-treatment and Drying Method on Colour Degradation Kinetics of Dried Salak Fruit During Storage

Sze Pheng Ong · Chung Lim Law · Ching Lik Hii

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Abstract Effect of heat treatment on colour stability of dried salak fruit during storage was investigated by using hot air (40–90 °C), heat pump (isothermal and intermittent modes, 26–37 °C) and freeze-drying. Influence of pre-treatment on the colour property was studied as well by blanching the sample at three levels of temperature (50–70 °C). Total colour change (ΔE^*) was used to assess the colour degradation kinetics and quantify the degree of browning during processing and storage. It was found that the dried pre-treated sample under heat pump isothermal drying recorded the highest ΔE^* value during storage followed by non-pre-treated samples under heat pump intermittent drying, freeze-drying, hot air-drying and heat pump isothermal drying. Weibull model is found to better fit the experimental data as compared with zero-order and first-order kinetics models. Analysis on the kinetics constants reveals that the heat treatment could affect the microstructure, water sorption properties and concentration of reacting species of the dried product. This in turn contributes to the colour changes of the dried product during storage.

Keywords Blanching · Freeze-drying · Hot air-drying · Heat pump-drying · Storage · Colour kinetics

Nomenclature

a^*	Colour parameter (dimensionless, positive value indicates red and negative value indicates green)
b	Weibull model's shape factor
b^*	Colour parameter (dimensionless, positive value indicates yellow and negative value indicates blue)
C	Value of colour parameter
ΔE^*	Total colour change (dimensionless)
k_0	Zero-order kinetic constant (1/month)
k_1	First-order kinetic constant (1/month)
k_a	Weibull kinetic constant (1/month)
L^*	Colour parameter (dimensionless, 0 for black to 100 for white)
R^2	Coefficient of determination
RMSE	Root mean square error
t	Storage time (month)

Greek letters

χ^2	Chi-square

Subscript

0	Initial value
∞	Equilibrium value after long storage period

Introduction

Colour is an important quality attribute in food products as it affects the visual appeal of the finished product as perceived by consumers. Changes of colour in food, in either positive or negative way, are a common phenomenon occurring during processing and storage. In fact, colour development is a result of various chemical and biochemical reactions that occur at cellular level. In general, discolouration is often accompanied by some other deleterious effects such as off-flavour development and loss of nutrients. Therefore, the loss of phytochemicals and other

S. P. Ong · C. L. Law (✉) · C. L. Hii
Department of Chemical and Environmental Engineering,
University of Nottingham Malaysia Campus,
Jalan Broga,
Semenyih, Selangor Darul Ehsan 43500, Malaysia
e-mail: chung-lim.law@nottingham.edu.my

nutrients in food can be closely related to the discolouration rate of the product.

Drying is an effective method to preserve agricultural products. Removal of moisture from fresh products may deactivate enzymes and microorganisms that often cause undesirable biochemical reactions in food, thus prolonging the shelf life of natural products (Fernandes et al. 2010; Mujumdar and Law 2010). However, thermal effect may destruct heat-sensitive substances in biological products and result in degradation of product quality, such as the colour, during drying process and in subsequent storage period. In most cases, the rates of discolouration often follow zero-order or first-order kinetics models, and the dependence of degradation rate constant on temperature can be described by Arrhenius-type equation (Goula et al. 2006; Koca et al. 2007; Lau et al. 2000; Saxena et al. 2010).

While extensive works have been carried out to investigate the effect of pre-treatment and drying method on discolouration rate of food product during processing (Aversa et al. 2009; Chong et al., 2008a; Chong et al., 2008b; Ganjloo et al. 2009; Gokhale and Lele 2010), study on colour stability during storage is very scarce particularly for heat pump-drying and intermittent drying. In a recent study, it was reported that browning rate in dried apple during storage could be closely related to microstructure modification during pre-treatment and drying (Acevedo et al. 2008). Meanwhile, degradation of important phytochemicals and nutrients in dried products was reported to correlate well with colour changes during storage (Arabhosseini et al. 2007; Niamnuy et al. 2008; Topuz et al. 2009). Hence, study on colour kinetics is essential in predicting product quality and minimising undesired changes of food property during storage. Besides the common kinetics models reported in literatures (e.g., the zero-order and first-order models), Weibull model has been proposed as an alternative approach to determining the browning rate and shelf life of food products (Corradini and Peleg 2004; Mizrahi 2004; Peleg et al. 2002). The model is also very useful in describing thermal degradation of heat-labile vitamins and colour pigments (Cunha et al. 1998; Odriozola-Serrano et al. 2009; Oms-Oliu et al. 2009a).

Salak fruit, or domestically known as snake fruit in Malaysia, is a peculiar fruit that can also be found in Indonesia, Thailand and the Philippines. Despite the unique taste and smell, salak fruit contains valuable bioactive antioxidants such as vitamin A, vitamin C and phenolic compounds (Leong and Shui 2002; Leontowicz et al. 2007; Setiawan et al. 2001). However, salak fruit has an inherent short shelf life of less than a week. Drying is therefore an option to preserve the fruit not only in dried form, but to retain the bioactive compounds that are beneficial to human health.

The objective of this study was to investigate the effect of pre-treatment (blanching), drying method (freeze-drying, hot air-drying and heat pump-drying) and drying mode (isothermal and intermittent drying) on colour stability of dried salak fruit during storage. Kinetics of total colour change (ΔE^*) was investigated to determine discolouration rate of dried salak fruit during storage.

Materials and methods

Sample preparation

Fresh salak fruit was purchased from a local fruit supplier (The Federal Agricultural Marketing Authority, Selayang, Selangor, Malaysia). Fruits with similar size (ca. 50–70× 50 mm) and skin colour (dark brown with average L^*, a^* and b^* values of 22.37±1.68, 1.05±0.90 and 8.66±2.11, respectively) were selected for all experiments. The fresh fruits were cleaned with a paper towel and kept in refrigerator at about 10 °C until experiments were conducted (with storage period no longer than 7 days). In each experiment, salak fruit was peeled and the cloves were separated. The individual cloves were cut longitudinally into equal halves, and the seeds at centre were removed. The halves were then cut to the required dimension and thickness (40×20×3 mm).

Pre-treatment

Pre-treatment was performed, when necessary, to inactivate potential enzyme activities (ascorbate oxidase and polyphenol oxidase) that may cause degradation of colour during drying and storage. Samples were blanched in hot water at 50 °C, 60 °C and 70 °C for 5 min, then immediately cooled under running cold water to stop further heating. Blanching water was drained, and excess water on sample surface was superficially dried with paper towel before subjected to drying. Relatively low blanching temperature (50–70 °C) was used because it could minimise the degradation of nutrition components and colour changes (Jayaraman and Das Gupta 2006; Ong and Law 2010a; Rahman and Perera 2007).

Drying procedure and measurements

Hot air-drying, freeze-drying and heat pump-drying were performed by using a laboratory-scale oven (Memmert, UFP500, Germany), a laboratory-scale freeze dryer (Martin Christ, Alpha 1–2 LD Plus, Germany) and a pilot-scale heat pump-assisted dryer prototype (I-Lab instrument, Malaysia), respectively. Basically, heat pump-drying is a type of convective drying but with lower air relative

humidity as compared with hot air-drying at same level of temperature. The heat pump-assisted dryer prototype (Fig. 1) consists of three main parts: a heat pump system, a heat recovery unit and drying chambers. The heat pump system is comprised of an evaporator (refrigerant R-22), a primary condenser (water-cooled), a secondary condenser (air-cooled), an expansion valve and a compressor. Moisture-laden air exhausted from drying chamber was first directed to the cool surface of evaporator where the air was cooled down to its saturated dew point and condensed. Temperature of the dehumidified air was then elevated by the hot water heat exchanger and an auxiliary heater (when higher temperature was required). A blower was used to supply constant forced air in the drying chambers.

Figure 2 illustrates the experimental works in this study while Table 1 shows the drying conditions and total drying time of the respective trials. Isothermal drying trials were performed at four levels of temperature in hot air-drying (HA40, HA50, HA70 and HA90) and two levels of temperature in heat pump-drying (HP26 and HP37). Two intermittent modes were investigated namely periodic heat supply (HP37HP37) and step-up air temperature (HP26HP37). Both have been reported to be efficient drying techniques in preserving the colour of dehydrated product (Chin and Law 2010; Chua et al. 2001b, 2002; Hii et al. 2011). For the periodic heat supply mode, dehumidified air at 37 °C and 17% RH was supplied to the drying chamber intermittently at 1-h intervals. Meanwhile, in the step-up temperature mode, dehumidified air at 26 °C (27% RH) was used in the initial stage of drying (the first 3 h), and the air temperature was increased to 37 °C (17% RH) thereafter until the fruit sample reached its equilibrium moisture content. Freeze-drying was performed at main drying temperature of −30 °C (coil temperature) for 24 h followed by final drying temperature of −50 °C (coil temperature) for 7 h. Fresh samples were frozen in a freezer (Ardo, S320, Italy) for at least 24 h before freeze-drying. For each drying trial, about 80 g of salak slices were arranged in thin-layer drying trays where another 20 g of random sample was placed separately in a sample holder that was made from wire mesh. With the exception of freeze-dried samples, weight loss of sample in the wire mesh holder was recorded hourly off-line until constant weight was obtained in three consecutive measurements by using a digital balance (Adventurer OHAUS, AR3130, USA). Moisture content at this stage was marked as the final moisture content (also known as equilibrium moisture content). Removing, weighing and returning of sample during the off-line weighing were performed in less than 15 s in order to avoid interference on the drying process (Janjai et al. 2008; Madamba et al. 1996; Özdemir and Onur Devres 1999; Wongwises and Thongprasert 2000). Dry matter weight was determined by drying the sample in an oven at 105 °C for 24 h, and water activity of dried sample was measured by using a water activity metre (Pawkit, Decagon, USA).

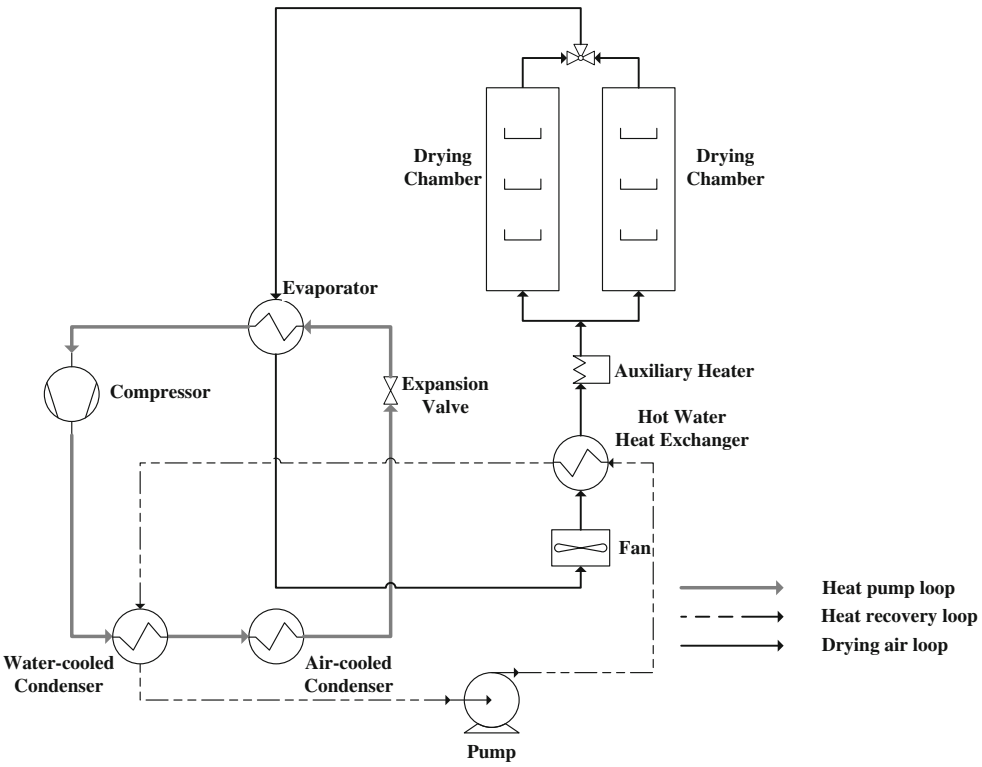

Fig. 1 Schematic of heat pump-assisted dryer

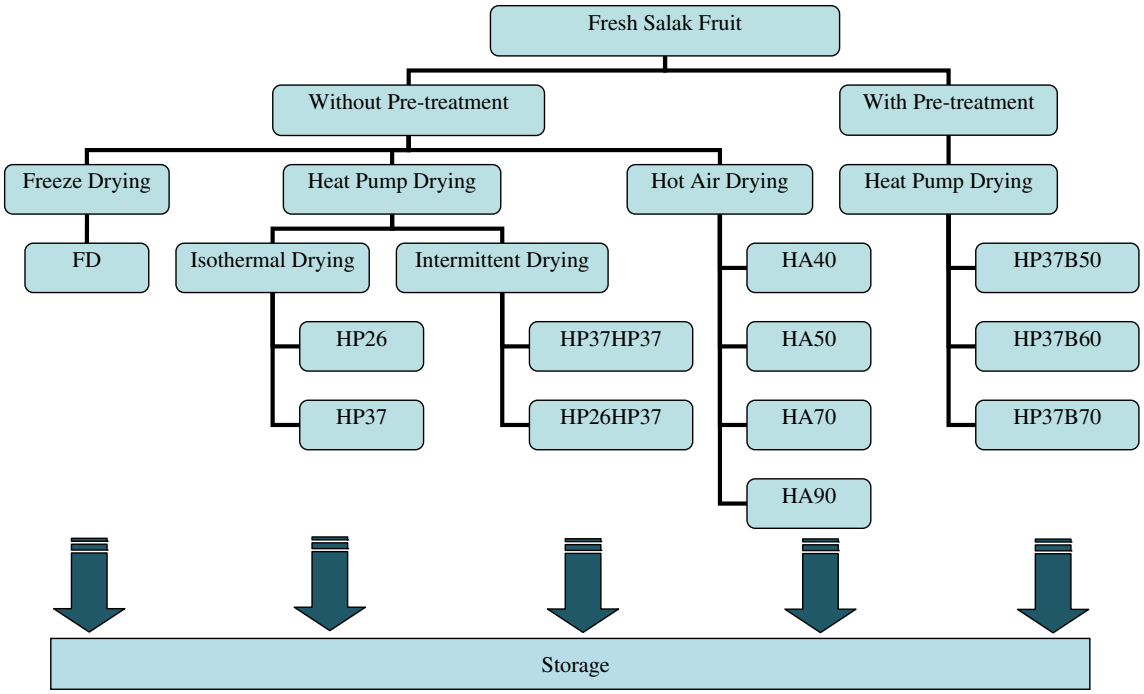

Fig. 2 Overview of the experimental works

Storage

About six to ten pieces of dried samples (selected randomly from bulk samples) were packed in a high-density polyethylene plastic bag with dimension of 135×76 mm and thickness of 60 μm. The plastic bag was then thermally sealed by using a heat sealer (Fei Ying, KS-100, China). The seal point was carefully examined to ensure proper sealing and no leakage. The samples were kept in dark at room temperature (25 °C, 55% RH) for up to 6 months, and colour analysis was performed at a monthly basis. At the end of storage, samples were analysed for final moisture content and water activity using a handheld water activity metre (Pawkit, Decagon, USA).

Colour measurement

Colour of dried salak was measured by using a handheld colour metre (AccuProbe, HH06, USA). About six pieces of dried samples were arranged in a Petri dish to form a thin-layer sheet that could cover the nosecone of the colour metre sensor. Nine measurements were taken at different

Table 1 Drying conditions and total drying time of respective drying trials

Drying method	Temperature (°C)	Relative humidity (%)	Time (h)
HA40	40±1	34±1	30
HA50	50±1	24±1	13
HA70	70±1	10±2	8
HA90	90±1	2±1	6
HP26	26±1	27±1	51
HP37	37±1	17±1	18
HP37HP37 (periodic heat supply mode)	37±1	17±1	22
HP26HP37 (step-up temperature mode)	26±1 (3 h),37±2 (12 h)	27±1 (3 h),17±1 (12 h)	15
HP37B50 (pre-treated at 50 °C)	37±1	17±1	15
HP37B60 (pre-treated at 60 °C)	37±1	17±1	11
HP37B70 (pre-treated at 70 °C)	37±1	17±1	10
FD	−30±1 (24 h),−50±1 (7 h)	nd	31

nd not determined

spots on both sides of the surface, by flipping over the samples when necessary, in order to get an average reading. Colours of the sample were indicated by CIELab colour scales L^*, a^* and b^*. Total colour change, ΔE^*, was calculated according to Eq. 1.

$$\Delta E^* = \left[\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2\right]^{1/2} \quad (1)$$

Kinetics models and parameters

Three kinetics models were evaluated in order to relate the colour change of product during storage to its heat treatment history. Zero-order kinetics model for the total colour change is shown in Eq. 2. Whilst adapted first-order kinetics model and Weibull model that incorporate with the concept of fractional conversion are shown in Eqs. 3 and 4, respectively (Oms-Oliu et al. 2009b; Topuz 2008; Topuz et al. 2009). Parameter b, which is temperature-independent in the Weibull model, indicates concavity or convexity of the kinetics curve when it takes value below and above unity, respectively (Corradini and Peleg 2004; Odriozola-Serrano et al. 2009).

$$\Delta E^* = \Delta E_0^* - k_0 t \quad (2)$$

$$\frac{\Delta E^* - \Delta E_\infty^*}{\Delta E_0^* - \Delta E_\infty^*} = \exp(-k_1 t) \quad (3)$$

$$\frac{\Delta E^* - \Delta E_\infty^*}{\Delta E_0^* - \Delta E_\infty^*} = \exp[-(k_a t)^b] \quad (4)$$

Modelling was carried out by performing nonlinear least-square regression with MS Excel SOLVER tool (Microsoft Office Professional 2003, USA). Statistical parameters such as coefficient of determination (R^2), chi-square (χ^2) and root mean square error (RMSE) were used as criteria to determine the goodness of fit. Model with the highest R^2 and lowest χ^2 and RSME values was chosen as the best model to describe the colour change kinetics of the dried sample during storage (Odriozola-Serrano et al. 2009).

Statistical analysis

All experiments were conducted as a completely randomised experiment and performed in triplicate. Data were analysed by using one-way ANOVA, and means comparisons were determined by Duncan Multiple Range Test at 95% confidence level using statistical software, SAS for Window (Version 9.1, SAS Institute, USA).

Results and discussion

Effect of pre-treatment and drying method on product colour before storage

The colour of fresh salak fruit is similar to fresh garlic, with average L^*, a^* and b^* values of 55.46±2.07, −3.27±0.36 and 27.96±0.60, respectively. Generally, browning effect was observed in all samples after drying. However, the browning indices varied among the dried samples depending on the pre-treatment temperature and drying method. Hot air-dried samples (HA40, HA50, HA70 and HA90) were darker and redder as compared with dried samples from other drying methods. It can be seen from Fig. 3 that ΔE^* values of the hot air-dried samples (7.30–32.06) increase significantly ($p<0.05$) with hot air temperature. The evolution of colour at the high drying temperature is probably caused by formation of a series of brown pigments, for instance, melanoindins, due to thermal effect (Maskan 2001).

On the other hand, colour of dried samples by heat pump-drying (HP26, HP37, HP37HP37 and HP26HP37) remained almost the same as the fresh fruit. With the exception of sample HP26, total colour change of the heat pump-dried samples was relatively low during drying as compared with the hot air-dried samples (Fig. 3). This suggests that heat pump-drying could preserve product colour better by avoiding serious Maillard browning reaction which often occurs at high temperature drying (Chua et al. 2000; Chua et al. 2001a).

Based on Fig. 3, it can be seen that ΔE^* values of dried samples from heat pump intermittent drying (HP37HP37 and HP26HP37) are significantly ($p<0.05$) lower than that in heat pump isothermal drying (HP26 and HP37). This could be due to the reduced heating period on the product by cutting off the heat flux during intermittent drying and hence diminish the browning effect. Nonetheless, when comparing the total colour change among the samples of heat pump isothermal drying, ΔE^* value of HP26 (8.17) is higher than HP37 (6.67). This is probably due to the longer drying time in HP26 as compared with HP37, even though drying temperature is lower in the former. The non-pre-treated sample (HP26) could have suffered from enzymatic browning during the long processing hours. On the contrary, total colour change of pre-treated samples (HP37B50, HP37B60 and HP37B70) is relatively low during drying. The results reveal that pre-treatment could minimise the enzymatic browning in samples effectively during drying. Nevertheless, the pre-treatment procedure needs to be improved in order to reduce the colour degradation that is incurred during the pre-treatment. It was found that total colour change of the dried pre-treated samples was partly contributed by the pre-treatment (prior

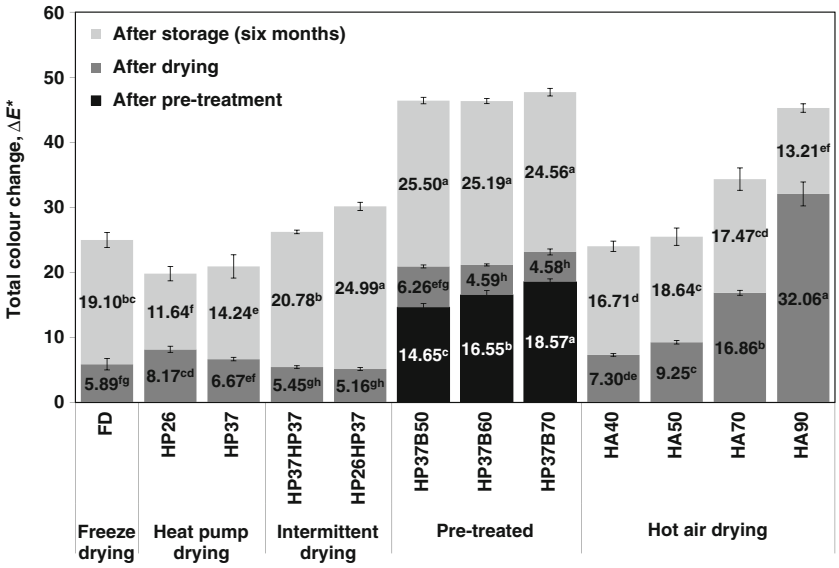

Fig. 3 Total colour change of salak fruit after pre-treatment, drying and storage (6 months). *Vertical bars above columns* denote standard errors. Mean values, within columns indicated by *same colour*, marked by *same letter* are not significantly different ($p>0.05$)

drying), where the ΔE^* values (14.65–18.57) had increased significantly ($p<0.05$) with blanching temperature. The colour degradation could be due to browning reactions that are caused by enzymatic activity after tissue disruption and prior to denaturation of enzymes in hot water.

Effect of pre-treatments and drying methods on product colour during storage

All dried samples turned darker and redder after 6 months storage with some light sour off-odour similar to a fermented plum. However, no formation of moulds or fungi was observed on the surface of the dried samples. Browning effects during storage were different among the dried samples depending on their heating history. Referring to Fig. 3, appreciable colour change was observed in all the dried pre-treated samples (HP37B50, HP37B60 and HP37B70) during storage, where significantly ($p<0.05$) high ΔE^* values (24.56–25.50) was detected. Apparently, although enzymes had been inactivated during pre-treatment, many other chemical reactions took place during storage. This could probably due to the higher proportion of cellular collapse and impaired cells that increase the effective release of reacting species in the pre-treated sample (e.g., amino acids, reducing sugars, ascorbic acid and phenolic compounds), thus facilitating the non-enzymatic browning reactions (Acevedo et al. 2008). On the other hand, noticeable total colour change was observed in samples of heat pump intermittent drying (HP37HP37 and HP26HP37) and freeze-drying (FD) as well, with ΔE^* values ranging from 20.78 to 24.99 and 19.10, respectively (Fig. 3). This could be due to the intrinsic moisture sorption properties of the dried samples. Freeze-dried and heat pump-dried products are hygroscopic and rehydrate faster as compared with others. Hence, the moisture content and water activity of these samples increase rapidly during storage. This in turn alleviates the diffusion of reacting species and promotes browning reactions (Labuza 1977). On the contrary, the ΔE^* values (11.64–14.24) of samples by heat pump isothermal drying (HP26 and HP37) was found to be relatively low as compared with other samples. This could be due to the mild temperature in the heat pump-drying that helps in maintaining integrity of cells and thus avoid some undesired enzymes and/or chemical activities that usually occur in broken cells. With the exception of sample HA90, the hot air-dried samples had shown higher ΔE^* values (13.21–18.64) as compared with the dried samples by heat pump isothermal drying. This could be due to the cellular collapses and tissue disruptions that occur during the high temperature processing. Total colour change in sample HA90 during storage was lower simply because of the lower concentration of reacting species prior storage due to high depletion rate in the drying process.

Table 2 shows the moisture content and water activity values of all dried samples before and after storage. It can be seen that moisture content and water activity values of all dried samples increased significantly after 6 months of storage. Basically, the high-density polyethylene plastic bag is a common packaging material for foods, but the film is water-vapour-permeable (Park 1999; Phillips 1996; Sandhya 2010; Techavises and Hikida 2008). At the same time, dried products tend to absorb moisture from the surrounding atmosphere due to their low equilibrium moisture content and hygroscopic properties. Hence, increment of moisture content and water activity in dried products is common during storage (Azeredo et al. 2006; Daramola et al. 2010; Kumar and Mishra 2004; Rahman et al. 2007). Nevertheless, moisture gaining rates were found different

Table 2 Moisture content and water activity values of dried samples before and after storage

Drying method	Moisture content, g water/g dry solid			Water activity, a_w	
	Before storage	After storage	Moisture gained %	Before storage	After storage
HA40	0.16 ± 0.01^{ab}	0.24 ± 0.01^{fg}	50%	0.55 ± 0.01^{ab}	0.65 ± 0.01^{a}
HA50	0.15 ± 0.01^{abc}	0.22 ± 0.04^{gh}	47%	0.53 ± 0.02^{bc}	0.65 ± 0.02^{a}
HA70	0.11 ± 0.01^{cd}	0.18 ± 0.03^{hi}	64%	0.52 ± 0.01^{cd}	0.63 ± 0.02^{ab}
HA90	0.09 ± 0.01^{d}	0.16 ± 0.02^{i}	78%	0.51 ± 0.01^{cd}	0.60 ± 0.02^{cd}
HP26	0.19 ± 0.05^{a}	0.28 ± 0.02^{def}	47%	0.51 ± 0.01^{cd}	0.62 ± 0.02^{bc}
HP37	0.13 ± 0.04^{bcd}	0.26 ± 0.01^{efg}	100%	0.50 ± 0.02^{de}	0.61 ± 0.01^{bc}
HP37HP37	0.15 ± 0.03^{abc}	0.33 ± 0.03^{abc}	120%	0.48 ± 0.01^{ef}	0.60 ± 0.02^{cd}
HP26HP37	0.15 ± 0.03^{abc}	0.35 ± 0.02^{a}	133%	0.47 ± 0.01^{f}	0.62 ± 0.01^{bc}
HP37B50	0.15 ± 0.01^{abc}	0.34 ± 0.01^{ab}	127%	0.57 ± 0.02^{a}	0.61 ± 0.01^{bc}
HP37B60	0.14 ± 0.03^{bc}	0.31 ± 0.03^{abcd}	121%	0.55 ± 0.01^{ab}	0.60 ± 0.01^{cd}
HP37B70	0.14 ± 0.01^{bc}	0.30 ± 0.02^{bcde}	114%	0.55 ± 0.02^{ab}	0.60 ± 0.01^{cd}
FD	0.12 ± 0.02^{bcd}	0.29 ± 0.03^{cde}	130%	0.35 ± 0.01^{g}	0.58 ± 0.01^{d}

Mean values within the same column marked by same letter are not significantly different ($p>0.05$).

among the dried samples. Moisture content of dried samples with pre-treatment (HP37B50, HP37B60 and HP37B70), heat pump intermittent drying (HP26HP37 and HP37HP37) and FD were found slightly higher as compared with other samples, with values ranging from 0.30 to 0.34, 0.33 to 0.35 and 0.29 g water/g dry solid, respectively. Meanwhile, lower moisture content was recorded in samples of heat pump isothermal drying (HP26 and HP37) and hot air-drying (HA40, HA50, HA70 and HA90), with values ranging from 0.26 to 0.28 and 0.16 to 0.24 g water/g dry solid, respectively. Apparently, the heating treatments had affected the moisture sorption characteristics of the dried products. This in turn resulted in different moisture gaining rates as well as discolouration rates during storage. Furthermore, it was observed that water activity values of all dried samples increased during storage. Basically, the increased water activity values were due to increased moisture content in the dried samples. It seems that the water activity values of the dried samples were within the range that is optimum for various deleterious reactions (0.55–0.65; Leung 1987; Ong and Law 2010b; Villamiel et al. 2006). Hence, degradation of colour during storage could be associated with moisture sorption properties of the dried samples.

Kinetics of total colour change ΔE*

Colour change of dried salak fruits was further studied by analysing the kinetics of the total colour change (ΔE^*) with reference to storage time. Increment in the ΔE^* value would depict the colour change of the dried sample from light yellow to dark brown colour. It can be seen from Fig. 4 that the ΔE^* values of all samples increase rapidly during the first few months of storage before reaching a plateau in the

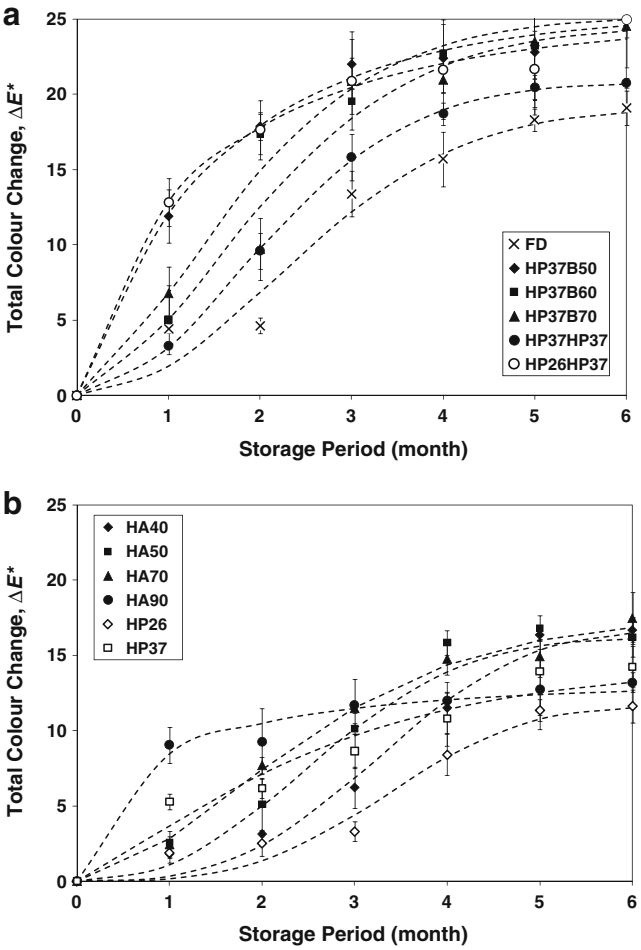

Fig. 4 Kinetics of ΔE^* during storage of samples of **a** freeze-drying, pre-treatment and intermittent drying **b** hot air-drying and heat pump-drying. *Dotted lines* are constructed based on Weibull model

later storage period. The slow colour development towards the end of storage is probably due to exhaustion of browning reaction substrates in sample after long storage period (Arabhosseini et al. 2007; Soliva et al. 2000). Furthermore, it can be seen from Fig. 4 that the ΔE^* values of dried samples evolve at different rates, although all dried samples were kept under the same storage conditions. The results show that the heat treatment history have significantly influenced the moisture sorption property as well as stability of phytochemicals in the dried samples and hence led to different degrees of colour change during storage. Table 3 presents the kinetic constants and respective R^2 values of parameter ΔE^* that were estimated from the zero-order, first-order and Weibull models. It is apparent that Weibull model could describe the kinetics of all the colour parameters better than zero-order and first-order models, with higher values in R^2 (0.949–1.000) and lower values in χ^2 (0.001–0.009; data not shown) and RMSE (0.008–0.080; data not shown).

Nevertheless, interpretation and comparison of the degradation kinetics across the samples based on Weibull's kinetic constants could be practically challenging. Both the scale factor (k_a) and shape factor (b) need to be considered simultaneously when examining the data. Basically, b constants in Weibull model would indicate that the kinetics curve of a colour parameter is either a tail-forming ($b<1$) or shoulder-forming ($b>1$) growth curve. Value of $b>1$ can be interpreted as increasing degradation over the entire storage period while $b<1$ indicates fast degradation in initial storage period but ceasing degradation in later period of storage (Buzrul and Alpas 2007; Buzrul et al. 2005; Oms-Oliu et al. 2009b). When magnitude of the b constant is decreasing, then a more pronounced tailing will be observed. Indirectly, the b constant would also indicate kinetics pattern of chemical events that occur at cellular level and controlling colour degradation (Peleg et al. 2002). It can be observed from Fig. 4 that ΔE^* value of sample HA90 increase rapidly in the first few months and then maintains at the maximum value over the remaining storage period. In accordance with the Weibull kinetic constants (Table 3), sample HA90 possesses the highest k_a value (1.038) and the lowest b value (0.629) which indicates rapid degradation at initial period and long-tailing at the later stage. Information on this kinetic pattern cannot be seen from the first-order model, although sample HA90 has recorded the highest k_1 value (0.818) as well in the first-order model. Nevertheless, it is worthy to note that HA90 has the lowest ΔE^* value during storage even though it has a high kinetic constant.

Referring to Table 3, b constant of Weibull model reveals that samples that were dried at higher temperature (e.g. HA70 and HA90) would possess higher degradation rates in colour during the initial storage period while samples that were dried at lower temperature (e.g. HA40 and HA50) would have lower degradation rates during the initial storage period. Similar result can be observed in samples by heat pump isothermal drying where b constant value of sample HP37 is lower than sample HP26. This could be due to the high temperature drying that led to broken cells in the samples and consequently resulted in instant oxidation and chemical reactions of the reacting species in the samples during storage. On the contrary, intact cells in samples that were processed at mild temperature might take some time to collapse and release the reacting species, thus delaying the browning reactions during storage.

Generally, kinetics of total colour change during storage is relatively high in all dried pre-treated samples (HP37B50, HP37B60 and HP37B70) with k_a values ranging from 0.407 to 0.616 and b values ranging from 0.922 to 1.633. The results show that the pre-treatment has

Table 3 Kinetic constants and R^2 values of parameter ΔE^* from zero-order, first-order and Weibull models

	Zero-order		First-order		Weibull		
	k_0	R^2	k_1	R^2	k_a	b	R^2
HA40	−2.803	0.939	0.268	0.806	0.270	3.050	0.984
HA50	−3.450	0.952	0.343	0.878	0.330	2.400	0.993
HA70	−3.196	0.949	0.358	0.941	0.348	1.640	0.993
HA90	−2.789	0.373	0.818	0.958	1.038	0.629	0.982
HP26	−1.947	0.918	0.267	0.786	0.266	3.340	0.956
HP37	−2.659	0.927	0.383	0.941	0.371	1.219	0.949
HP37HP37	−4.086	0.919	0.419	0.927	0.395	1.938	1.000
HP26HP37	−5.009	0.549	0.611	0.982	0.659	0.783	0.991
HP37B50	−5.170	0.606	0.603	0.992	0.616	0.922	0.993
HP37B60	−5.016	0.779	0.482	0.951	0.465	1.509	0.979
HP37B70	−4.811	0.878	0.431	0.928	0.407	1.633	0.968
FD	−3.548	0.938	0.354	0.889	0.336	2.047	0.964

induced adverse impact on the sample colour development, although it is designed to inactivate enzymatic browning during long period of drying and storage. It seems that blanching in hot water has resulted in denaturation of cell membranes and bursting of cell walls that consequently led to release of reacting species in the cell tissues and thus facilitating non-enzymatic browning during storage (Acevedo et al. 2008; Aguilera and Stanley 1999; Bondaruk et al. 2007). On the contrary, the dried non-pre-treated sample (HP37) under the same drying condition has lower degradation kinetics during storage as compared with the dried pre-treated sample (HP37B50, HP37B60 and HP37B70) with k_a and b values of 0.371 and 1.219, respectively. Therefore, the pre-treatment procedure needs to be improved (e.g. shorter blanching time) or even excluded, as it has caused serious browning in the sample during blanching and storage. Pre-treatment is not necessary in the present study as the enzymatic browning effect is not significant under the heat pump isothermal drying.

Conclusions

Colour changes of dried salak fruit during storage is closely related with its heat treatment history. Pre-treatment and drying conditions could significantly affect the microstructure, concentration of reacting species and moisture sorption of products which in turn influence the stability of product colour during storage period. It was found that freeze-drying produced dried products with minimum colour change, but the colour degradation rate of the freeze-dried samples during storage was relatively high. Hot air-dried samples (except 40 °C) experienced severe colour change during drying as well as during storage (except 90 °C). As a result, total colour change of hot air-dried samples especially those dehydrated at high temperature gave relatively high overall total colour change. Although pre-treated samples showed minimal colour change during drying, the sample experienced significant colour change during pre-treatment and also in the subsequent storage period. Therefore, the overall total colour change for all pre-treated samples has high overall total colour change. Dried samples by heat pump intermittent drying possessed appealing product colour after drying, but colour degradation rates were quite high during storage. On the other hand, isothermal heat pump-dried samples have relatively low total colour change in drying as well as in storage, and thus gave low overall total colour change if compared with all samples. Therefore, heat pump isothermal drying could be considered as a good drying method for the fruit processing industry, particularly salak fruit if overall colour change during drying and storage is of main concern. Weibull model was found to be a better kinetics model as compared with the zero-order and first-order models. It is very useful in estimating the colour degradation kinetics during storage.

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