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Effect of different rehydration temperatures on the moisture, content of phenolic compounds, antioxidant capacity and textural properties of edible Irish Brown seaweed

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Abstract

The effect of temperature (20, 40, 60, 80 and 100 °C) on the rehydration kinetics and phytochemical constituents of dried edible Irish brown seaweed, *Himanthalia elongata*, were studied. The moisture content of fresh and dried seaweed was 4.07 and 0.07 g water/g dry basis, representing a 98.1 % reduction in water content. All rehydration moisture curves had a clear exponential tendency, and it was observed that the rehydration time decreased when temperature was increased. Although restoration of the product to its original moisture content was achieved, rehydration resulted in losses in phytochemical content. Moisture equilibrium was achieved fastest at 100 °C (40 min) with losses of 83.2 and 93 % in the total phenol and total flavonoid contents, respectively. The moisture content was fitted to empirical kinetic models; Weibull, Peleg's, first-order and exponential association. Activation energies of 4.03, 4.28 and 3.90 kJ/mol were obtained for the parameters of Peleg's, first-order and exponential models, respectively.

Keywords: Seaweed, *Himanthalia elongata*, rehydration, antioxidants, modelling.

Nomenclature

α, β, k_1,k_2, k_{R1} and k_{R2}	Parameters in the models
Ea	Activation energy for moisture diffusion (kJ/mol)
RR	Rehydration ratio
R^2	Co-efficient of determination
RMSE	Root mean square error
SS	Sum square error
T	Drying temperature (Kelvin)
t	Drying time (h)

W	Moisture content at any time (g H_2O/ g dry basis)
W_e	Equilibrium moisture content (g H_2O/ g dry basis)
W_o	Initial moisture content (g H_2O/ g dry basis)
$X\ (t)$	Instantaneous moisture content (kg water/kg dry matter)
X_0	Initial moisture content (kg water/kg dry matter)
χ^2	Chi square

1. Introduction

Seaweeds have been utilized since ancient times as foods in the Far East and Asia and are the raw material for industrial production of agar, carrageenan and alginates. Marine algae contain various kinds of inorganic and organic substances which can benefit human health such as polyphenols, carotenoids and tocopherols (Chanda, Dave, Kaneria, & Nagani, 2010). The marine environment in which seaweeds grow is harsh as they are exposed to a combination of light and high oxygen concentrations. These factors can lead to the formation of free radicals and other strong oxidizing agents but seaweeds seldom suffer any serious photodynamic damage during metabolism. This fact implies that their cells have some protective antioxidative mechanisms and compounds (Matsukawa, Dublinsky, Kishimoto, Masaki, & Takeuchi, 1997). Seaweeds provide an excellent source of bioactive compounds such as antioxidants, dietary fibre, essential fatty acids, vitamins and minerals (Jiménez-Escrig & Goni, 1999; Chandini, Ganesan, & Bhaskar, 2008). Consumption of seaweeds increases the intake of dietary fibre and lowers the occurrence of some chronic diseases (diabetes, obesity, heart diseases and cancers) which are associated with low fibre diets of the Western countries (Southgate, 1990).

Being marine in nature seaweeds contain a large amount of water, 75 – 85 % and as they are perishable in their fresh state and can deteriorate within a few days of harvest; drying is an

essential step before they can be used in industrial processing (Gupta, Cox, & Abu-Ghannam, 2011). The traditional way to preserve these plant products is by sun drying. Drying helps to retard microbial growth, reduce the bulk handling thereby facilitating transportation and allows their use during the off-season (Mota, Luciano, Dias, Barroca, & Guiné, 2009). However, other processes, promoted by high temperatures, can occur simultaneously with moisture removal during drying, resulting in undesirable alterations of certain characteristics of the material, such as shrinkage and color changes (enzymatic and non-enzymatic browning) (Maskan, 2001). During air-drying, spatial conformation of components of food material can be partially altered by water flux. In addition, there is a partial destruction of tissue structure, which results in water permeability, consequently rehydration ability can also decrease, and changes in the texture (Krokida, Karathanos, & Maroulis, 2000; Lewicki & Jakubczyk, 2004).

Dehydrated food products are usually rehydrated before consumption. Rehydration is a complex process intended to restore the properties of the fresh product by contacting dehydrated products with a liquid phase. The process is composed of three simultaneous steps: (1) absorption of water into the dry material, (2) swelling of the rehydrated product, and (3) loss or diffusion of soluble components (Marin, Lemus, & Flores, 2006; Lee, Farid, & Nguang, 2006). Typically, a higher rate of water absorption is observed during initial stages which then decline until equilibrium is achieved. Water temperature is the most important factor influencing the rehydration and generally more rapid rehydration is obtained at higher water temperatures. Treatments such as drying and rehydration produce changes in the structure and composition of product tissues. Gupta et al. (2011) found that drying of *H. elongata* at 25 °C resulted in 49 % and 51 % reduction in the total phenol and total flavonoid content, respectively, as compared to fresh seaweed. Rehydration or blanching is carried out to make vegetables more palatable but studies have shown that phenolic compounds are

sensitive to heat, whereby blanching and boiling of vegetables for few minutes could cause a significant loss of phenolic content which can leach into boiling water (Amin, Norazaidah, & Hainida, 2006). Since seaweeds are most commonly consumed after rehydration, it is important to investigate the effect of rehydration on the phytochemicals which are present. Mathematical models of dehydration and rehydration are important to the design and optimization of these processing conditions. Empirical equations frequently used to model the rehydration kinetics of foods include Weibull, Peleg's, first order and exponential association models (Peleg, 1988; Krokida & Marinos-Kouris, 2003; Sacchetti, Pittia, Biserni, Pinnavaia, & Rosa, 2003). The study of rehydration kinetics helps in process optimization and gives valuable information about the effect of process variables. The present work aimed to study the rehydration kinetics of *Himanthalia elongata* at a range of temperatures (20, 40, 60, 80 and 100 ºC). The effect of the rehydration conditions on the content of phenolic compounds, antioxidant capacity and textural properties of the seaweed was also evaluated. These objectives are justified having in mind that the literature lacks some information on the rehydration kinetics of seaweeds in terms of empirical models.

2. Methods

2.1 Seaweed material

H. elongata was purchased from Quality Sea Veg., Co Donegal, Ireland. Samples were collected in August 2010, washed thoroughly with freshwater to remove epiphytes and stored at -18 °C until analysis.

2.2 Drying procedure

Fresh seaweeds were washed and cut manually with stainless steel knife into rectangular samples of approximately 3 cm × 0.5 cm × 0.2 cm. Five gram samples were weighed and

placed on a flat tray and dried in a hot air incubator (Innova 42, Mason Technology, Ireland) at 40 °C for 24 hours. The incubator has a 2.0 ± 0.1 m/s air velocity as measured with VWR Enviro-meter digital anemometer (VWR, Ireland). The dry solids content was determined by employing control samples using an oven at 105 °C until constant weight of the sample was attained. The relative humidity was monitored with a data logger Grant 1001.

2.3 Rehydration procedure

Dried seaweed samples were rehydrated by immersion in 2 L of distilled water kept at the specified rehydration temperatures (20, 40, 60, 80 and 100 °C) using a water bath (Lauda, Aqualine AL5, Mason Technology, Ireland). Samples were removed every 5 minutes until a constant weight was achieved. After rehydration, the seaweeds were drained using a wire mesh strainer, blotted with tissue paper to remove surface water and placed on ice to cool before the extraction procedure.

2.4 Extraction of phytochemicals

The extraction of phenolic compounds from *H. elongata* was carried out with 60 % methanol under nitrogen atmosphere as reported in our previous studies (Cox, Abu-Ghannam, & Gupta, 2010).

2.5 Total phenolic content

The total phenolic concentration (TPC) was measured using the Folin-Ciocalteau method (Taga, Miller & Pratt, 1984). The total phenolic contents were expressed as g gallic acid equivalent per 100 gram dry basis (db) (mg GAE/100 g db).

2.6 Total flavonoid content

Total flavonoid contents (TFC) were determined according to the method of Zhishen, Mengcheng, & Jianming, (1999). Quercetin was used to prepare the standard curve and results were expressed as g quercetin equivalents (QE)/100 gram db (mg QE/100 g db).

2.7 DPPH radical scavenging activity

The free radical scavenging activity was measured by 2, 2-Diphenyl-1-picrylhydrazyl (DPPH) according to the method of Yen & Chen (1995) with some modifications as described in our previous studies (Gupta et al., 2011).

2.8 Texture evaluation

Instrumental texture analysis was carried out for all of the seaweed samples withdrawn. Shear tests were performed using an Instron Universal Testing Machine (Model 4301, Canton MA, USA) supported with Bluehill 2 version 2.14 analysis software for materials testing. An aluminium Warner Bratzler attachment with dimensions of 10 x 6 cm^2, thickness 1.3 cm and an opening of 3 mm in the centre was used in the shear tests. Seaweed samples (5 g) were sheared at a speed of 200 mm/min. The shearing implement was allowed to travel the depth of the seaweed, cutting through the sample and seaweed hardness was defined as the peak of force-deformation curve recorded in Newtons per mm (N/mm).

2.9 Scanning electron microscopy

The structure of the seaweed samples (fresh, dried and rehydrated) were obtained with a scanning electron microscope (Hitachi SU6600, Hitachi High-Technologies Europe GmbH, Germany). The samples were first ground into fine powder form and then suspended in ethanol to obtain a 1 % suspension. The suspension was sprinkled on double stick tape fixed

on an aluminium stub, and the starch was coated with gold: palladium (60:40). An accelerating potential of 5 kV was used during micrography.

2.10 Rehydration kinetics expressed in terms of empirical models

Different mass transfer mechanisms such as diffusion and capillary flow have been proposed to describe the rehydration process, but the exact mechanism is not known. Thus empirical models, being simplistic in terms of their mathematical application, are most frequently used for describing the rehydration kinetics. The data obtained experimentally for the five different temperatures studied (20, 40, 60, 80 and 100 °C) were plotted in the form of the dimensionless variable rehydration ratio (RR) versus time (expressed in min). RR was calculated as follows:

$$\text{Rehydration ratio (RR)} = \frac{X(t)}{X_0} \quad \text{Eq. 1}$$

Where: $X(t)$ and X_0 are the instantaneous and initial moisture contents on dry basis respectively.

The experimental sets (RR Vs time, *t*) were fitted to four different empirical models from the literature, shown in Table 1, using STATGRAPHICS Centurion XV (StatPoint Technologies, Inc., Warrenton, VA). In order to prove the temperature dependence of the rate constant (k), the Arrhenius equation was applied, graphically representing *ln k* versus 1/T (Simal, Femenía, Gerau, & Roselló, 2005).

2.11 Statistical analysis

All experiments were performed in triplicate and replicated twice. All statistical analyses were carried out using STATGRAPHICS Centurion XV (StatPoint Technologies, Inc.,

Warrenton, VA). Differences were considered statistically significant when $p < 0.05$. The goodness of fit of the tested mathematical models to the experimental data was evaluated from the coefficient of determination (R^2), Sum square error (SSE; Eq. 2), root mean square error (RMSE; Eq. 3) and the chi-square (χ^2; Eq. 4) between the predicted and experimental values.

$$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(RR_{exp} - RR_{pred}\right)^2 \quad \text{Eq. 2}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(RR_{exp} - RR_{pred}\right)^2} \quad \text{Eq. 3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(RR_{exp,i} - RR_{pred,i}\right)^2}{N-z} \quad \text{Eq. 4}$$

Where: $RR_{exp,i}$ is the experimental rehydration ratio, $RR_{pred,i}$ is the predicted rehydration ratio, N is the number of observations and z is the number of constants.

3. Results and Discussion

3.1 Effect of rehydration conditions on moisture content

Seaweeds are perishable in their fresh state and deteriorate within a few days of harvest and are dried outdoors under atmospheric conditions as a means of preservation. Dried seaweeds are commonly rehydrated in hot water before consumption therefore the present study aimed to observe the rehydration procedure of dried *H. elongata* over a wide range of temperatures. In our previous studies, the effect of drying temperatures on moisture and phytochemical content was studied (Gupta et al., 2011). It was found that 40 °C was the optimal drying temperature in terms of phytochemical content and was applied in the present study. The dried seaweed samples were rehydrated at 20, 40, 60, 80 and 100 ºC until the moisture

content reached equilibrium (up to 80 min) to investigate the effect of temperature on rehydration kinetics.

The initial moisture content of the fresh seaweed was 4.07 ± 0.02 g water/g db and the dried seaweed contained 0.074 ± 0.01 g water/g db, representing a 98.1 % reduction in water content/g db. Fig. 1 shows the variation of moisture content as a function of time for the five rehydration temperatures. All rehydration curves show a clear exponential tendency, and as expected, the rehydration time decreased when the temperature increased until all the samples reached similar equilibrium moisture content. As rehydration time progressed, there was a decrease in the driving force for water transfer and the system slowly attained equilibrium. Higher temperatures resulted in an increase in the magnitude of absorbed water. For example, at 20 ºC rehydration reached equilibrium at 75 min while equilibrium was reached after 65, 55 and 45 min at 40, 60 and 80 °C, respectively. Increasing the temperature to 100 ºC increased the rate of water absorption and equilibrium was attained after 40 min, representing 46.6 % reduction in the rehydration time as compared to rehydration at 20 °C.

It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption. Often there can be irreversible cellular rupture and dislocation, resulting in loss of integrity and hence, a dense structure of collapsed, greatly shrunken capillaries with reduced hydrophilic properties can occur. This is reflected by the inability to imbibe sufficient water to rehydrate fully (Krokida & Marinos-Kouris, 2003). Seaweeds grow in distinct vertical bands on the seashore and it is well known that their ability to recover physiological processes following desiccation is correlated to their shore position. Despite this, little is known of the cellular mechanisms by which intertidal seaweeds limit membrane damage during desiccation and subsequent rehydration. An ability to tolerate desiccation is therefore a prerequisite for their survival (Burritt, Larkindal, & Hurd, 2002). The dried seaweed samples in the present study had the ability to rehydrate with final moisture contents

248 equal or higher to that of the fresh seaweed. This indicates that the hydrophilic properties had
249 the ability to imbibe sufficient water at all of the working temperatures which is of great
250 benefit. Not all plants have the ability to be dried and rehydrate to their original capacity, for
251 example, Vega-Gálvez, Notte-Cuello, Lemus-Mondaca, & Miranda, (2009) found that aloe
252 vera could only achieve a maximum rehydration capacity of 38 % of the original product.
253 In order to describe the rehydration kinetics of seaweed, four empirical models; Weibull,
254 Peleg's, first-order and exponential association were applied (Table 1). All of the models
255 used provided a good agreement with the experimental data. The R^2 values (Table 2) ranged
256 from 0.9807 to 0.9985 for the different models. Fig. 2 shows the predicted and experimental
257 points obtained for the five temperatures for each of the four different models (Weibull (a),
258 Peleg's (b), First-order (c) and Exponential (d)). From the results obtained it can be verified
259 that all four of the models applied in this study showed a good predicting capacity, and
260 revealed good performance for the temperatures tested over the entire rehydration procedure.
261 First-order rehydration kinetic model had the lowest R^2 values among the four models.
262 The examination of the parameters obtained from the models applied (Table 3) showed that
263 the scale parameter (β) of the Weibull model, kinetic rate constant k_1 and characteristic
264 constant k_2 of the Peleg's model are changing inversely proportional to the rehydration
265 temperature applied. On the other hand, the kinetic constants of first-order (k_{R1}) and
266 exponential association models (k_{R2}) are increasing with increased rehydration temperature.
267 Parameter k_2 of the Peleg's model decreases as the temperature increases which was also
268 reported by Vaga-Gálvez et al. (2009) for aloe vera. Solomon (2007) suggested that this
269 parameter is related to maximum capacity of water absorption or to equilibrium moisture
270 content, in such a way that lowest values of k_2 show a higher water absorption capacity.
271 Therefore the results show that water absorption capacity increases as water rehydration
272 temperature increases. Similar trends were observed by Maskan (2002) and Moreira, Chenlo,

Chaguri, & Fernandes, (2008) for wheat and chestnuts. Moreover, time taken to reach equilibrium moisture content of the dried seaweed samples (*We*) decreased as the rehydration temperature increased which shows that higher temperatures are more effective in reaching a maximum rehydration capacity in shorter times. Table 3 also shows the values of parameters α and β of the Weibull model, where temperature has no linear influence on parameter α. However, parameter β decreases as temperature is increased. Similar behaviour was reported by Machado, Oliveria, Gekas, & Singh, (1998) and Cunningham, McMinn, Magee, & Richardson, (2007) for puffed breakfast cereals and pasta, respectively. These authors suggested that parameter β represents the time needed to accomplish approximately 63 % of the rehydration process.

3.2 Estimation of activation energy for kinetic constants

In order to prove the dependence of the *k* parameters; k_1, k_{R1} and k_{R2} of the models, Peleg's, first-order and exponential on temperature, respectively, the Arrhenius equation was applied graphically represented by *ln k* versus 1/T (Simal et al., 2005). Plots showed a linear relationship with regression coefficients (R^2) of 0.8889, 0.9314 and 0.9339 for Peleg's, first-order and exponential models, respectively, verifying the dependence of rehydration on temperature. From the slopes activation energies of 4.03, 4.28 and 3.90 kJ/mol were obtained for the parameters of Peleg's, first-order and exponential models, respectively.

3.3 Effect of rehydration on the phytochemical constituents

The bioavailability of phytochemicals is influenced by the matrix and microstructure of the food they occur in, the storage conditions (light, oxygen, and temperature regime) and thermal processing they are subjected to. As a consequence, knowledge of the content and stability of phytochemicals in foods after processing is essential to evaluate the nutritional

298 value of foods rich in these phytochemicals such as seaweed. Since seaweed would need to
299 undergo some hydrothermal treatment in order to rehydrate prior to consumption, it was
300 relevant to assess the effects of rehydration treatment on the stability of seaweed antioxidant
301 properties. In our previous studies, it was reported that extracts from *H. elongata* have high
302 antioxidant activity (Cox et al., 2010). Drying of *H. elongata* at 40 ºC for 24 hours results in a
303 decrease in the phytochemicals up to 29 % (Gupta et al., 2011). The TPC was monitored for
304 *H. elongata* rehydrated at different temperatures every 10 minutes over the duration of the
305 rehydration process (Fig. 3a). The initial content of TPC of the dried seaweed was 1.21 ±
306 0.02 g GAE/100 g db. Rehydration resulted in a steep decrease in TPC of dried seaweed
307 within the first 10 minutes at each of the tested temperatures. As was previously discussed,
308 rehydrating the dried seaweed at 100 ºC increased the rate of water absorption and
309 equilibrium moisture was attained after 40 min. At this time the TPC of the seaweed was 0.2
310 ± 0.009 g GAE/100 g db. Studies have shown that phenolic compounds are sensitive to heat,
311 whereby boiling of vegetables for few minutes could cause a significant loss of phenolic
312 content which can leach into blanching water (Amin et al., 2006). Bunea et al. (2008)
313 reported a 50 % loss of TPC in spinach blanched for 10 min.
314 Fig. 3b shows the variation in the TFC for the five temperatures studied. The TFC in the
315 dried seaweeds was 0.49 ± 0.016 g QE/100 g db. Rehydration led to a reduction in TFC
316 which was proportional to the increase in time and temperature. Reductions in the range of
317 88.3 - 93.2 % in TFC were seen at 20, 40, 60, 80 and 100 ºC, respectively at the end of 60
318 min. The fastest equilibrium moisture content was reached at a temperature of 100 °C for 40
319 min with a 93 % reduction in TFC. Release of flavonoids and increased chemical extraction
320 of these compounds could be induced by the effect of boiling (Olivera et al., 2008). This
321 release of flavonoids coupled with contact and leaching into water could have resulted in high

322 reduction in TFC for boiled samples. The results of the present study are similar to Olivera et
323 al. (2008) who found that boiling decreased TFC in brussels sprouts.
324 The antioxidant capacity of dried and rehydrated *H. elongata* was determined by the DPPH
325 radical scavenging assay tested at a concentration of 50 µg/ml (Fig. 3c). Dried *H. elongata*
326 extract had a DPPH radical scavenging activity of 75.7 %. For all of the rehydration
327 temperatures (20, 40, 60, 80 and 100 ºC) the radical scavenging activity increased in the
328 range of 13.2 – 24.3 % up to 20 min of treatment, after which it decreased but at the time of
329 equilibrium (75, 65, 55, 45 and 40 min for 20, 40, 60, 80 and 100 °C, respectively) the
330 activity decreased. However, the activity was still higher than that of dried seaweed. The
331 highest percentage increase was seen in seaweed rehydrated at 80 ºC which increased to 100
332 % after 20 min (24.3 % increase). These results show that there is a temperature dependence
333 in the case of antioxidant activity. It has been reported that blanching positively affects the
334 radical scavenging activity in other foods, and Rossi et al. (2003) showed that blanching
335 strongly lowered the signal amplitude of DMPO-OH radical adduct in comparison with an
336 unblanched sample using electron paramagnetic resonance (EPR) spectroscopy, hence
337 increasing its activity.
338 Every thermal process is detrimental to the integrity of plant tissue, particularly cellular
339 membranes; thus, temperature increases above the optimum could lead to damage in the
340 matrix leading to variations in its response to the process being applied. Accordingly,
341 increasing rehydration temperature causes a deterioration of texture that compounds the
342 damage caused during thermal dehydration and promotes significant loss of mechanical
343 resistance in the samples. This excess softening of tissues alters mass transfer ability of the
344 system. During rehydration, sugars solubilise and molecules become more mobile, which
345 increase solid loss throughout the processing time. If the temperature is raised these effects
346 are intensified (Maldonado, Arnau, & Bertuzzi, 2010). The texture of the seaweed (Fig. 4)

softened significantly over the rehydration process for each of the temperatures studied ($p < 0.05$). The force required to break the initial dried seaweed was 85.0 N/mm. The texture change varied in the range of 43.0 to 25.6 N/mm upon rehydration with the greatest reduction seen at the highest temperature of 100 ºC. The trend of reduction in phytochemicals varied in accordance with the reduction in texture for each of the rehydration temperatures. Besides the water uptake, during the rehydration process there is also a soluble solid loss, which could produce significant losses of vitamins, sugars, amino acids and minerals (García-Pascual, Sanjuán, Melis, & Mulet, 2006).

Image analysis was carried out on the fresh, dried and rehydrated seaweed tissues using scanning electron microscopy (SEM) analysis as in Fig. 5. An image of fresh *H. elongata* can be observed in Fig. 5a; the structure became flattened, sightly collapsed and shrinkage in the fronds was observed upon drying (Fig. 5b). The number of open structures and pores became considerably lesser upon drying. Seaweed rehydrated at 100 °C for 40 min (equilibrium moisture content) can be seen in Fig. 5c. In this case, the structure of the rehydrated seaweed has become more swollen in comparison to fresh and dried *H. elongata* which could be attributed to the significant texture change upon rehydration of the seaweed at such high temperatures. García-Segovia, Andrés-Bello, & Martínez-Monzó (2011) reported similar structural findings in rehydrated mushroom.

Conclusion

This study showed that the rehydration kinetics of *H. elongata* can be accurately predicted using the empirical models of Weibull, Peleg's, first-order and exponential association. The temperature dependence of the rehydration procedure was shown to follow an Arrhenius relationship. Overall, restoration of the product to its original moisture content was achieved however there were significant losses in phytochemical content during the rehydration

procedure. Moisture equilibrium was achieved most quickly at 100 °C after 40 min. Under these rehydration conditions, losses of 83.2 and 93 % were seen in the TPC and TFC, respectively, as compared to dried seaweed. Since dried seaweeds are generally rehydrated prior to consumption, the present study clearly shows that the process of drying and subsequent rehydration can significantly reduce the phytochemicals present in seaweeds. Thereby it is important to find out novel methods of rehydration which could prevent the destruction of these important properties of seaweeds.

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Table 1. Empirical models used for the fitting of rehydration kinetics of *H. elongata* at different temperatures

Model name	Equation
Weibull	RR = $We + (Wo - We) \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right]$
Peleg	RR = $W_o + \frac{t}{k_1 + k_2 t}$
First-order rehydration kinetic model	RR = $W_e + (W_0 - W_e)\exp(-k_{R_1} t)$
Exponential association model	RR = $W_e[1 - \exp(-k_{R_2} t)]$

Table 2. Statistical indices upon modelling the rehydration of *H. elongata* at a range of temperatures

Model	Temperature (°C)	SSE	RMSE	$\chi 2$	R^2
Weibull	20	0.01	0.1002	0.0106	0.9922
	40	0.0086	0.093	0.0091	0.9918
	60	0.0062	0.079	0.0067	0.9948
	80	0.0077	0.0882	0.0083	0.9936
	100	0.0018	0.0425	0.0019	0.9985
Peleg	20	0.0158	0.1257	0.0168	0.9878
	40	0.006	0.0775	0.006	0.9943
	60	0.005	0.0709	0.0054	0.9958
	80	0.0065	0.0806	0.007	0.9947
	100	0.0051	0.0714	0.0054	0.9959
First-order rehydration kinetic model	20	0.0216	0.1472	0.023	0.9833
	40	0.0315	0.7321	0.0335	0.9945
	60	0.0232	0.1525	0.025	0.9807
	80	0.0238	0.1545	0.0257	0.9806
	100	0.0086	0.0927	0.0092	0.9931
Exponential association model	20	0.0308	0.1755	0.0327	0.9936
	40	0.0269	0.1642	0.0286	0.9895
	60	0.0292	0.171	0.0022	0.9925
	80	0.0275	0.1659	0.0296	0.9907
	100	0.0092	0.0963	0.0099	0.9926

Table 3. Results of fitting of rehydration kinetics to the four models (values in curved brackets are the standard error and values in square brackets are 95 % confidence intervals)

Model	Parameter	20 °C	40 °C	60 °C	80 °C	100 °C
Weibull	*We*	5.027 (±0.445) [4.064-5.99]	4.224 (±0.094) [4.019-4.428]	4.335 (±0.131) [4.041-4.629]	4.336 (±0.129) [4.047-4.625]	4.25 (±0.311) [4.181-4.32]
	Wo	0.049 (±0.113) [-0.196-0.295]	-0.002 (±0.106) [-0.232-0.227]	0.005 (±0.093) [-0.203-0.213]	0.005 (±0.104) [-.0226-0.237]	0.017 (±0.05) [-0.094-0.129]
	α	0.671 (±0.076) [0.505-0.837]	0.638 (±0.066) [0.495-0.782]	0.62 (±0.066) [0.471-0.769]	0.636 (±0.073) [0.472-0.801]	0.766 (±0.037) [0.684-0.849]
	β	30.209 (±7.589) [13.814-46.605]	9.124 (±0.942) [7.025-11.224]	9.07 (±0.812) [7.316-10.824]	8.754 (±0.908) [6.73-10.777]	7.334 (±0.256) [6.762-7.906]
Peleg	*Wo*	0.163 (±0.126) [-0.107-0.435]	0.0044 (±0.084) [-0.179-0.182]	0.013 (±0.079) [-0.16-0.188]	0.01 (±0.09) [-0.187-0.209]	0.001 (±0.08) [-0.174-0.178]
	k_1	3.927 (±0.459) [2.942-4.913]	1.414 (± 0.102) [1.123-1.564]	1.312 (±0.096) [1.099-1.525]	1.27 (±0.105) [1.037-1.502]	1.079 (±0.079) [0.904-1.254]
	k_2	0.222 (±0.004) [0.213-0.233]	0.2198 (±0.004) [0.210-0.229]	0.218 (±0.004) [0.207-0.228]	0.215 (±0.004) [0.206-0.225]	0.195 (±0.006) [0.181-0.208]
First-order rehydration kinetic model	*We*	4.297 (±0.104) [4.073-4.522]	4.0269 (±0.037) [4.003-4.141]	4.032 (±0.064) [3.89-4.175]	4.071 (±0.065) [3.927-4.214]	4.163 (±0.037) [4.08-4.246]
	Wo	0.318 (±0.133) [0.031-0.605]	0.129 (±0.1) [-0.19-0.265]	0.116 (±0.164) [-0.246-0.48)	0.113 (±0.167) [-0.255-0.481]	0.095 (±0.101) [-0.127-0.317]
	k_{R1}	0.0447 (±0.004) [0.035-0.053]	0.103 (±0.011) [0.093-0.142)	0.119 (±0.011) [0.094-0.145]	0.12 (±0.006) [0.105-0.135]	0.13 (±0.007) [0.114-0.146]
Exponential association model	*We*	4.211 (±0.056) [4.147-4.392]	4.0175 (±0.04) [3.953-4.132]	4.024 (±0.048) [3.994-4.213]	4.063 (±0.048) [4.008-4.226]	4.159 (±0.036) [4.078-4.239]
	k_{R2}	0.0512 (±0.002) [0.043-0.053]	0.108 (±0.007) [0.106-0.138]	0.122 (±0.006) [0.106-0.137]	0.124 (±0.007) [0.108-0.141]	0.134 (±0.006) [0.119-0.148]

*We, Wo, α, β, k_1,k_2, k_{R1} and k_{R2} are the model parameters

Legends to the figures

Fig. 1: Experimental rehydration curves of *H. elongata* at different temperatures (◊: 20 °C; □: 40 °C; Δ: 60 °C; ○: 80 °C; ×: 100 ºC)

Fig. 2: Experimental and predicted rehydration curves for (a) Weibull; (b) Peleg's; (c) First order and (d) Exponential models for the five temperatures (◊: 20 °C; □: 40 °C; Δ: 60 °C; ○: 80 °C; ×: 100 ºC)

Fig. 3: Effect of drying temperatures on the (a) total phenolic content and (b) total flavonoid content of *H. elongata*. Results are expressed as per 100 g db. (c) DPPH radical scavenging activity of *H. elongata*. Results are expressed as % scavenging. (◊: 20 °C; □: 40 °C; Δ: 60 °C; ○: 80 °C; ×: 100 ºC)

Fig. 4: Effect of drying temperatures on the texture of *H. elongata*

Fig. 5: SEM of *H. elongata* tissue (a) fresh, (b) dried at 40 °C, 24 hours and (c) rehydrated at 100 °C, 40 min

Fig. 1

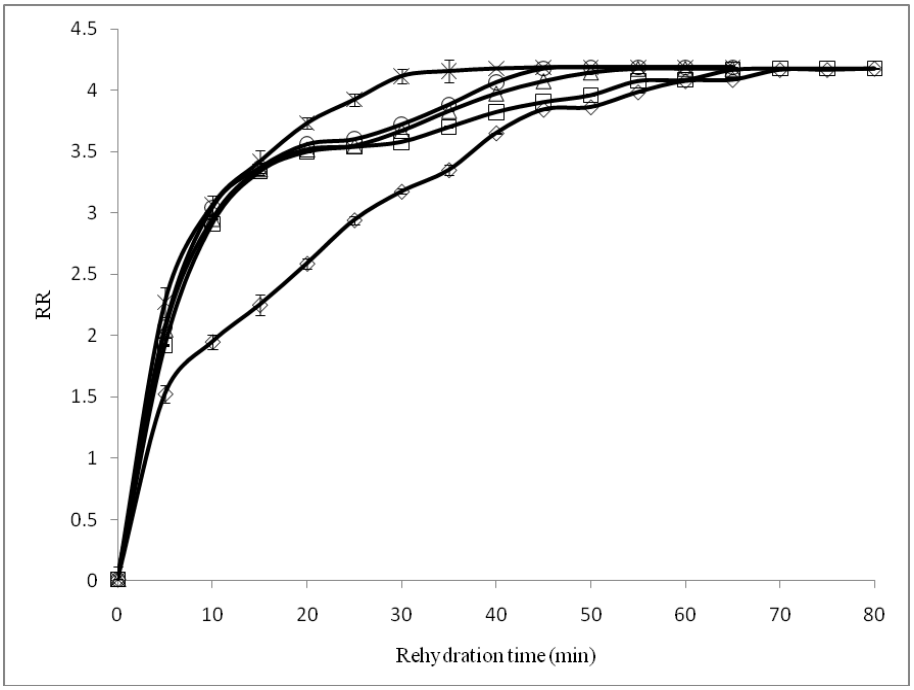
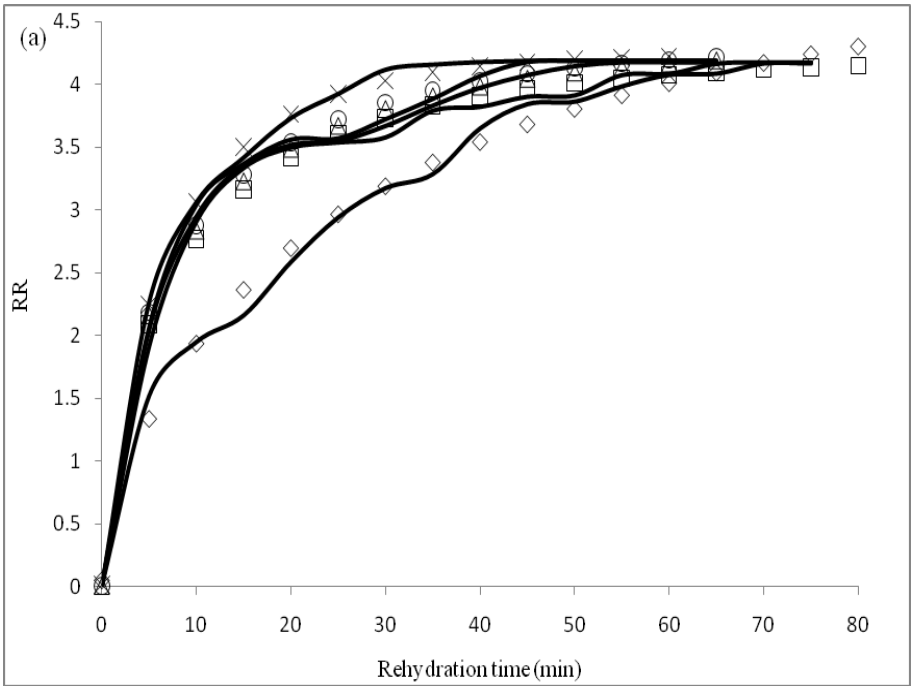
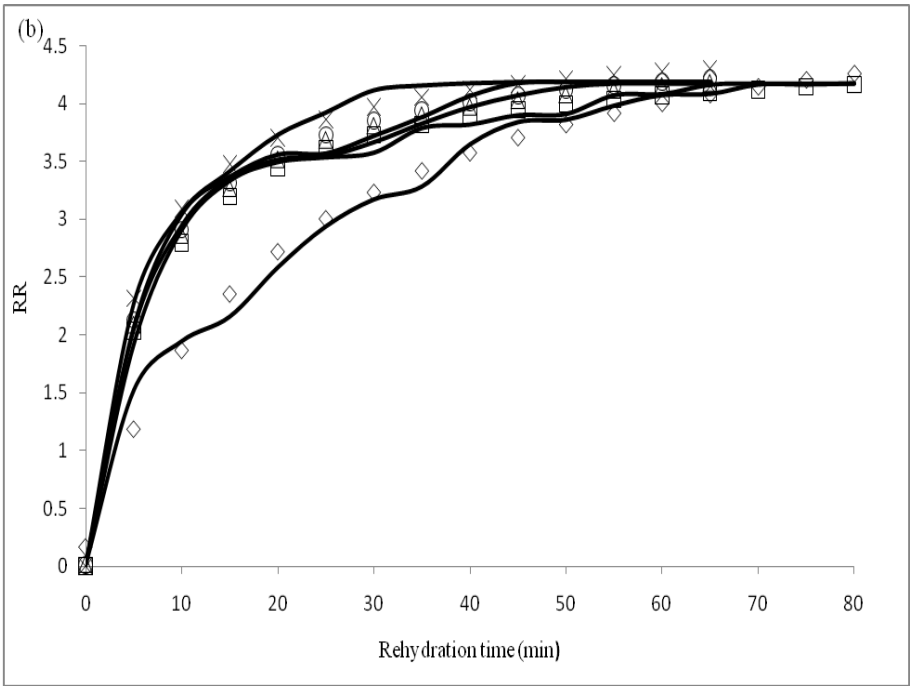
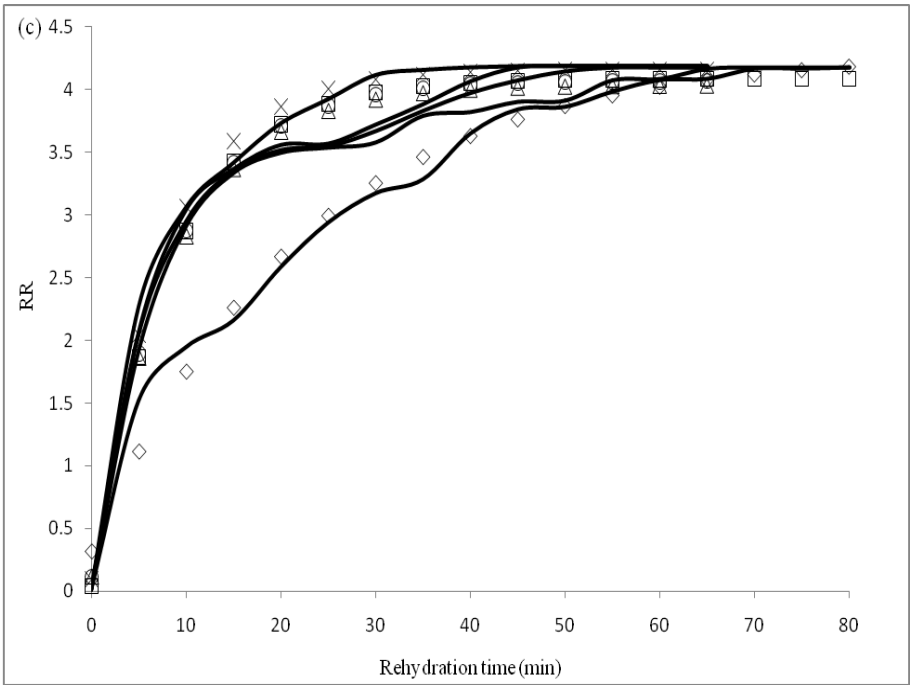

RR
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
Rehydration time (min)

Fig. 2


(a)
RR
Rehydration time (min)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
10
20
30
40
50
60
70
80


(b)
RR
Rehydration time (min)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
10
20
30
40
50
60
70
80


(c)
RR
Rehydration time (min)

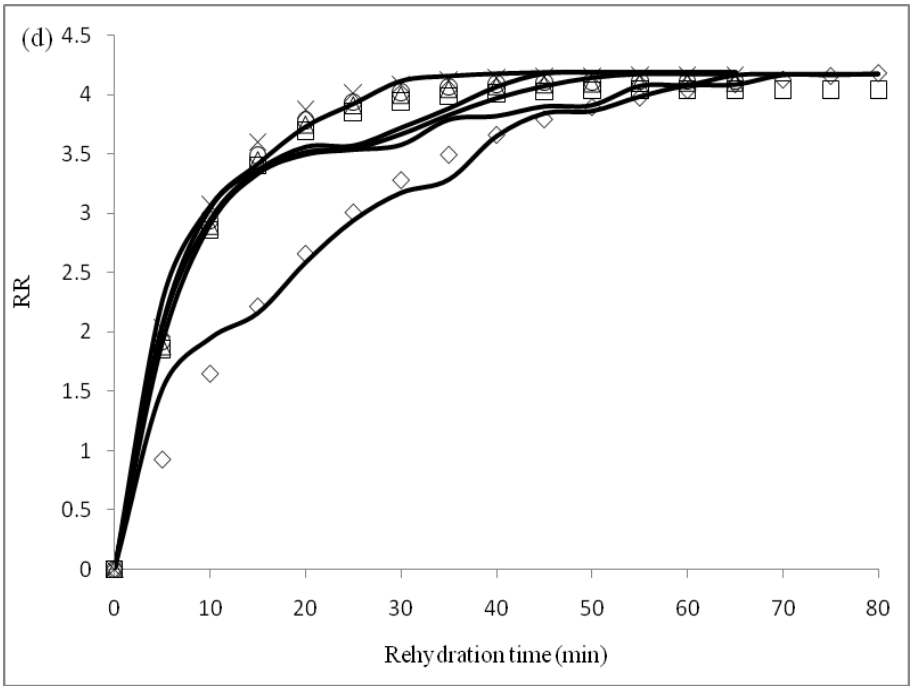
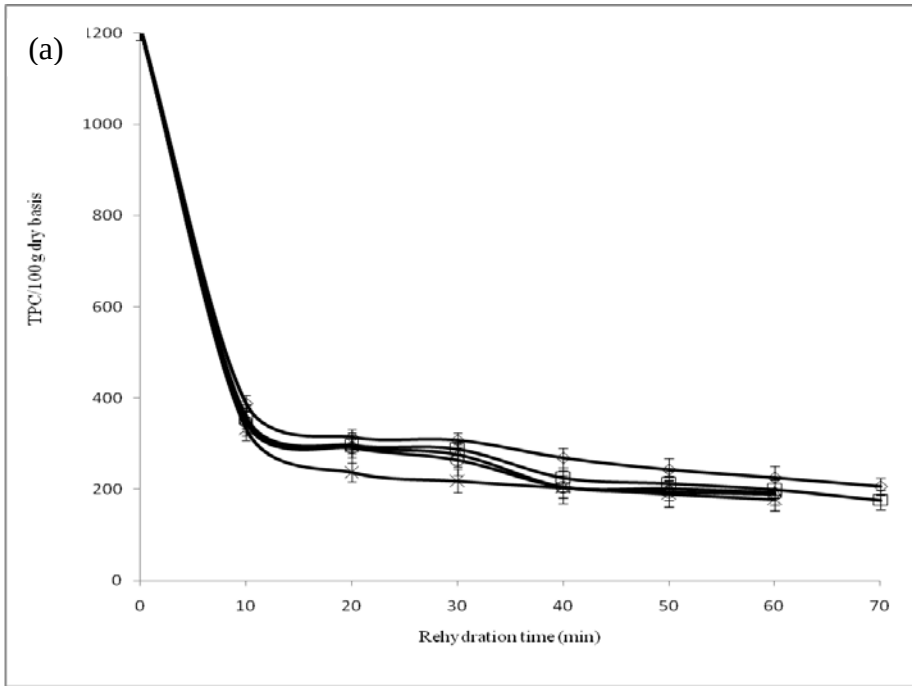
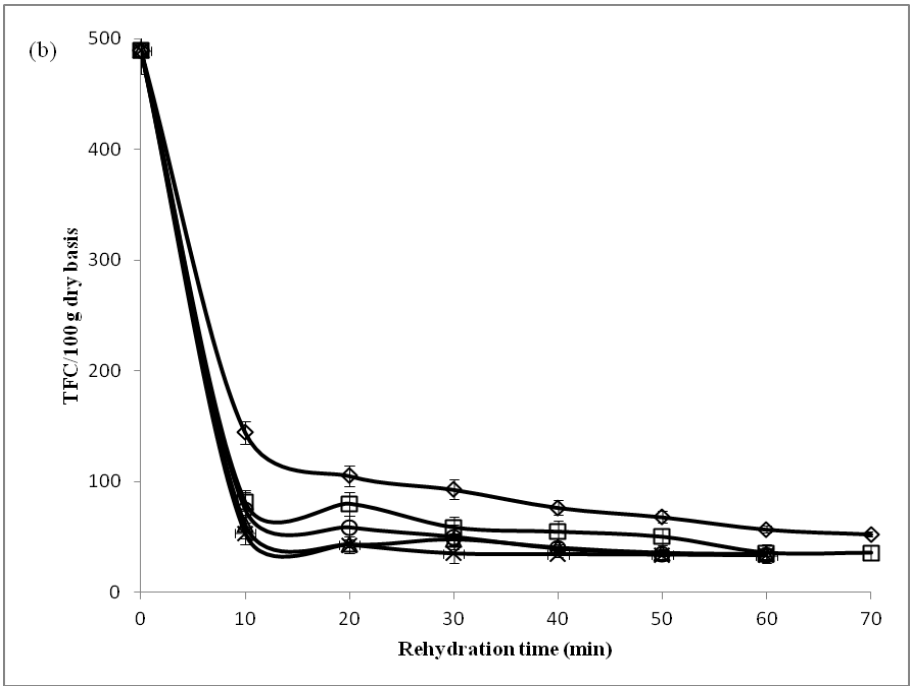

(d)
RR
Rehydration time (min)

Fig. 3


(a)
1200
1000
800
600
400
200
0
TPC/100 g dry basis
0
10
20
30
40
50
60
70
Rehydration time (min)


(b)
500
400
300
200
100
0
TFC/100 g dry basis
0
10
20
30
40
50
60
70
Rehydration time (min)

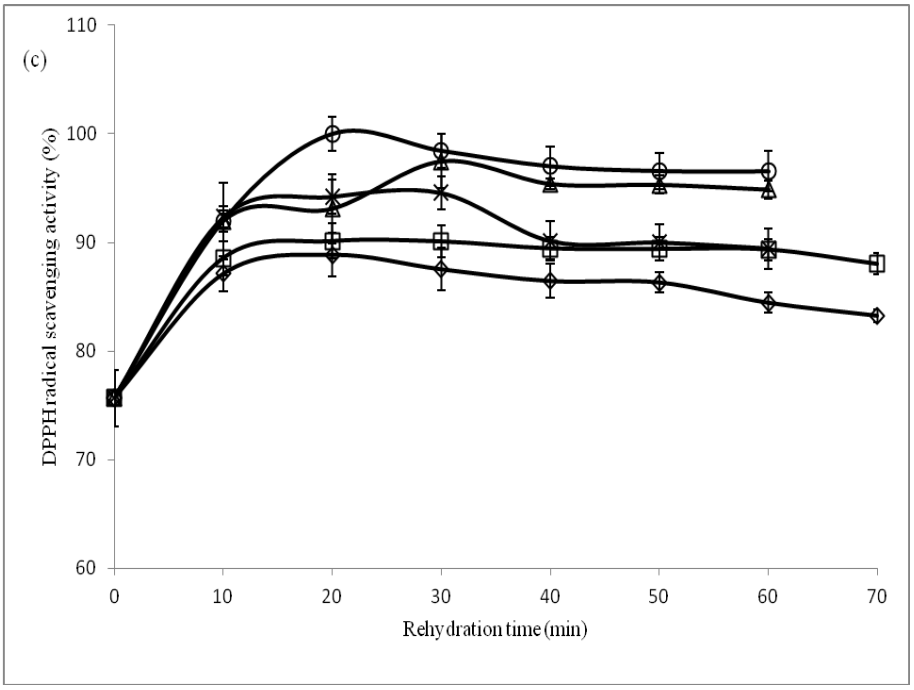

(c)
DPPH radical scavenging activity (%)
110
100
90
80
70
60
0
10
20
30
40
50
60
70
Rehydration time (min)

Fig. 4

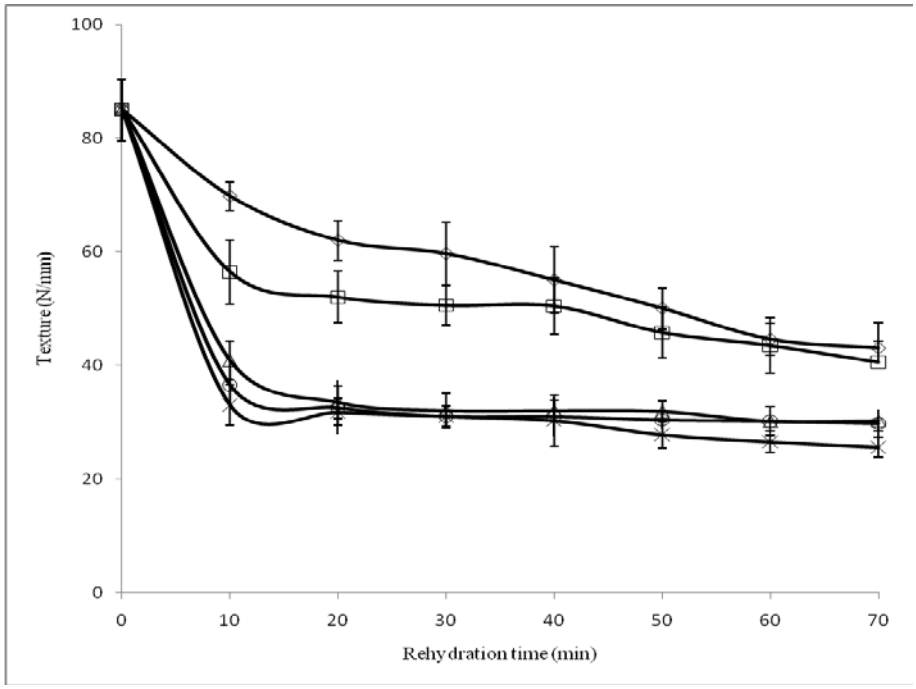
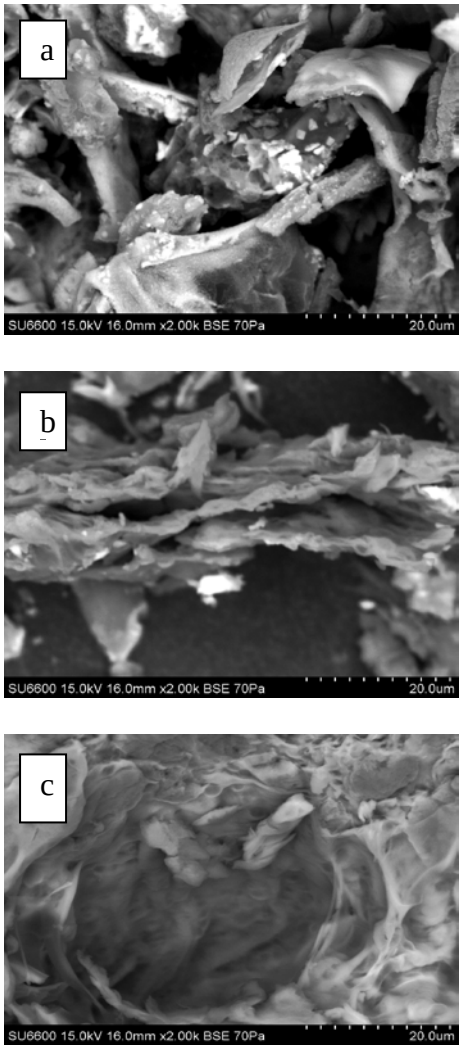

100
80
60
40
20
0
Texture (N/mm)
0
10
20
30
40
50
60
70
Rehydration time (min)

Fig. 5


a
SU6600 15.0kV 16.0mm x2.00k BSE 70Pa
20.0um
b
SU6600 15.0kV 16.0mm x2.00k BSE 70Pa
20.0um
c
SU6600 15.0kV 16.0mm x2.00k BSE 70Pa
20.0um