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Effect Of Different Rehydration Temperatures On The Moisture And Phytochemical Constituents Of Dried Edible Irish Brown Seaweed.

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

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26 **Abstract**

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

39
40 **Keywords:** Seaweed, *Himanthalia elongata*, rehydration, antioxidants, modelling.

41 42 **Nomenclature**

43 $\alpha, \beta, k_1, k_2, k_{R1}$ and k_{R2}	Parameters in the models
44 Ea	Activation energy for moisture diffusion (kJ/mol)
45 RR	Rehydration ratio
46 R^2	Co-efficient of determination
47 RMSE	Root mean square error
48 SS	Sum square error
49 T	Drying temperature (Kelvin)
50 t	Drying time (h)

51	W	Moisture content at any time (g H ₂ O/ g dry basis)
52	W_e	Equilibrium moisture content (g H ₂ O/ g dry basis)
53	W_o	Initial moisture content (g H ₂ O/ g dry basis)
54	$X(t)$	Instantaneous moisture content (kg water/kg dry matter)
55	X_o	Initial moisture content (kg water/kg dry matter)
56	χ^2	Chi square

57

58 **1. Introduction**

59 Seaweeds have been utilized since ancient times as foods in the Far East and Asia and are the
60 raw material for industrial production of agar, carrageenan and alginates. Marine algae
61 contain various kinds of inorganic and organic substances which can benefit human health
62 such as polyphenols, carotenoids and tocopherols (Chanda, Dave, Kaneria, & Nagani, 2010).

63 The marine environment in which seaweeds grow is harsh as they are exposed to a
64 combination of light and high oxygen concentrations. These factors can lead to the formation
65 of free radicals and other strong oxidizing agents but seaweeds seldom suffer any serious
66 photodynamic damage during metabolism. This fact implies that their cells have some
67 protective antioxidative mechanisms and compounds (Matsukawa, Dublinsky, Kishimoto,
68 Masaki, & Takeuchi, 1997). Seaweeds provide an excellent source of bioactive compounds
69 such as antioxidants, dietary fibre, essential fatty acids, vitamins and minerals (Jiménez-
70 Escrig & Goni, 1999; Chandini, Ganesan, & Bhaskar, 2008). Consumption of seaweeds
71 increases the intake of dietary fibre and lowers the occurrence of some chronic diseases
72 (diabetes, obesity, heart diseases and cancers) which are associated with low fibre diets of the
73 Western countries (Southgate, 1990).

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

76 essential step before they can be used in industrial processing (Gupta, Cox, & Abu-Ghannam,
77 2011). The traditional way to preserve these plant products is by sun drying. Drying helps to
78 retard microbial growth, reduce the bulk handling thereby facilitating transportation and
79 allows their use during the off-season (Mota, Luciano, Dias, Barroca, & Guiné, 2009).
80 However, other processes, promoted by high temperatures, can occur simultaneously with
81 moisture removal during drying, resulting in undesirable alterations of certain characteristics
82 of the material, such as shrinkage and color changes (enzymatic and non-enzymatic
83 browning) (Maskan, 2001). During air-drying, spatial conformation of components of food
84 material can be partially altered by water flux. In addition, there is a partial destruction of
85 tissue structure, which results in water permeability, consequently rehydration ability can also
86 decrease, and changes in the texture (Krokida, Karathanos, & Maroulis, 2000; Lewicki &
87 Jakubczyk, 2004).

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

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

116

117 **2. Methods**

118 **2.1 Seaweed material**

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

122

123 **2.2 Drying procedure**

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

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

131

132 **2.3 Rehydration procedure**

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

139

140 **2.4 Extraction of phytochemicals**

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

144

145 **2.5 Total phenolic content**

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

149

150 **2.6 Total flavonoid content**

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

154

155 **2.7 DPPH radical scavenging activity**

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

159

160 **2.8 Texture evaluation**

161 Instrumental texture analysis was carried out for all of the seaweed samples withdrawn. Shear
162 tests were performed using an Instron Universal Testing Machine (Model 4301, Canton MA,
163 USA) supported with Bluehill 2 version 2.14 analysis software for materials testing. An
164 aluminium Warner Bratzler attachment with dimensions of 10 x 6 cm², thickness 1.3 cm and
165 an opening of 3 mm in the centre was used in the shear tests. Seaweed samples (5 g) were
166 sheared at a speed of 200 mm/min. The shearing implement was allowed to travel the depth
167 of the seaweed, cutting through the sample and seaweed hardness was defined as the peak of
168 force-deformation curve recorded in Newtons per mm (N/mm).

169

170 **2.9 Scanning electron microscopy**

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

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

177

178 **2.10 Rehydration kinetics expressed in terms of empirical models**

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

186

$$187 \text{ Rehydration ratio (RR)} = \frac{X(t)}{X_0} \quad \text{Eq. 1}$$

188

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

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

196

197 **2.11 Statistical analysis**

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

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

205

$$206 \quad SSE = \frac{1}{N} \sum_{i=1}^N (RR_{exp} - RR_{pred})^2 \quad \text{Eq. 2}$$

$$207 \quad RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (RR_{exp} - RR_{pred})^2} \quad \text{Eq. 3}$$

$$208 \quad \chi^2 = \frac{\sum_{i=1}^N (RR_{exp,i} - RR_{pred,i})^2}{N-z} \quad \text{Eq. 4}$$

209

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

212

213 **3. Results and Discussion**

214 **3.1 Effect of rehydration conditions on moisture content**

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

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

225 The initial moisture content of the fresh seaweed was 4.07 ± 0.02 g water/g db and the dried
226 seaweed contained 0.074 ± 0.01 g water/g db, representing a 98.1 % reduction in water
227 content/g db. Fig. 1 shows the variation of moisture content as a function of time for the five
228 rehydration temperatures. All rehydration curves show a clear exponential tendency, and as
229 expected, the rehydration time decreased when the temperature increased until all the samples
230 reached similar equilibrium moisture content. As rehydration time progressed, there was a
231 decrease in the driving force for water transfer and the system slowly attained equilibrium.

232 Higher temperatures resulted in an increase in the magnitude of absorbed water. For example,
233 at 20 °C rehydration reached equilibrium at 75 min while equilibrium was reached after 65,
234 55 and 45 min at 40, 60 and 80 °C, respectively. Increasing the temperature to 100 °C
235 increased the rate of water absorption and equilibrium was attained after 40 min, representing
236 46.6 % reduction in the rehydration time as compared to rehydration at 20 °C.

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

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

283

284 **3.2 Estimation of activation energy for kinetic constants**

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

292

293 **3.3 Effect of rehydration on the phytochemical constituents**

294 The bioavailability of phytochemicals is influenced by the matrix and microstructure of the
295 food they occur in, the storage conditions (light, oxygen, and temperature regime) and
296 thermal processing they are subjected to. As a consequence, knowledge of the content and
297 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 °C 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 $1.21 \pm$
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 °C 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 °C, 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 °C) 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 °C 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)

347 softened significantly over the rehydration process for each of the temperatures studied ($p <$
348 0.05). The force required to break the initial dried seaweed was 85.0 N/mm. The texture
349 change varied in the range of 43.0 to 25.6 N/mm upon rehydration with the greatest reduction
350 seen at the highest temperature of 100 °C. The trend of reduction in phytochemicals varied in
351 accordance with the reduction in texture for each of the rehydration temperatures. Besides the
352 water uptake, during the rehydration process there is also a soluble solid loss, which could
353 produce significant losses of vitamins, sugars, amino acids and minerals (García-Pascual,
354 Sanjuán, Melis, & Mulet, 2006).

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

365

366 **Conclusion**

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

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

379

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

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

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

Model	Temperature (°C)	SSE	RMSE	χ^2	R²
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	<i>We</i>	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]
	<i>Wo</i>	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	<i>Wo</i>	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]
	<i>k</i> 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]
	<i>k</i> 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	<i>We</i>	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]
	<i>Wo</i>	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]
	<i>k</i> _{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	<i>We</i>	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]
	<i>k</i> _{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 (\diamond : 20 °C; \square : 40 °C; Δ : 60 °C; \circ : 80 °C; \times : 100 °C)

Fig. 2: Experimental and predicted rehydration curves for (a) Weibull; (b) Peleg's; (c) First order and (d) Exponential models for the five temperatures (\diamond : 20 °C; \square : 40 °C; Δ : 60 °C; \circ : 80 °C; \times : 100 °C)

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. (\diamond : 20 °C; \square : 40 °C; Δ : 60 °C; \circ : 80 °C; \times : 100 °C)

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

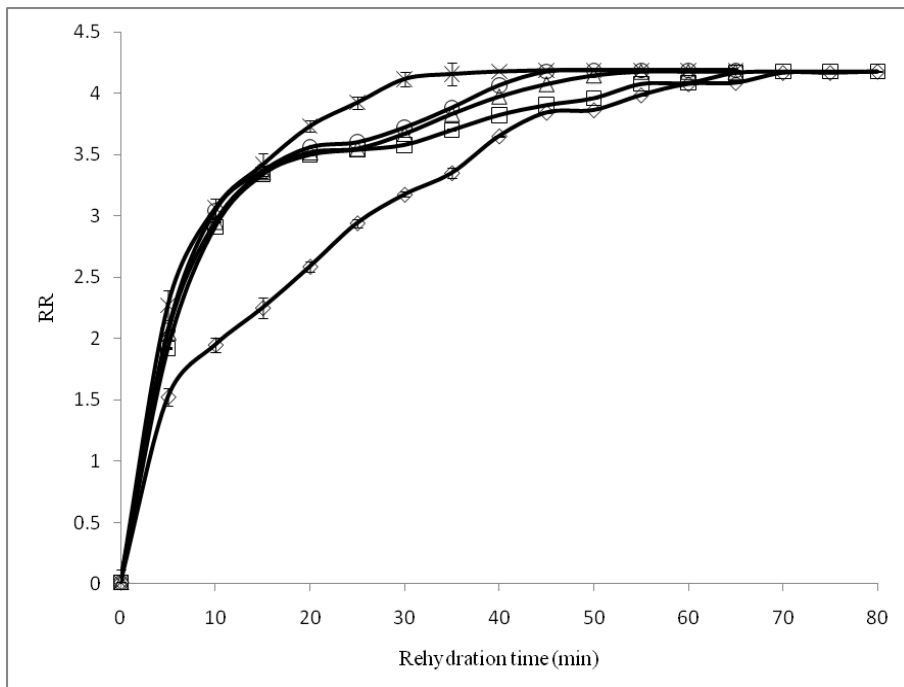
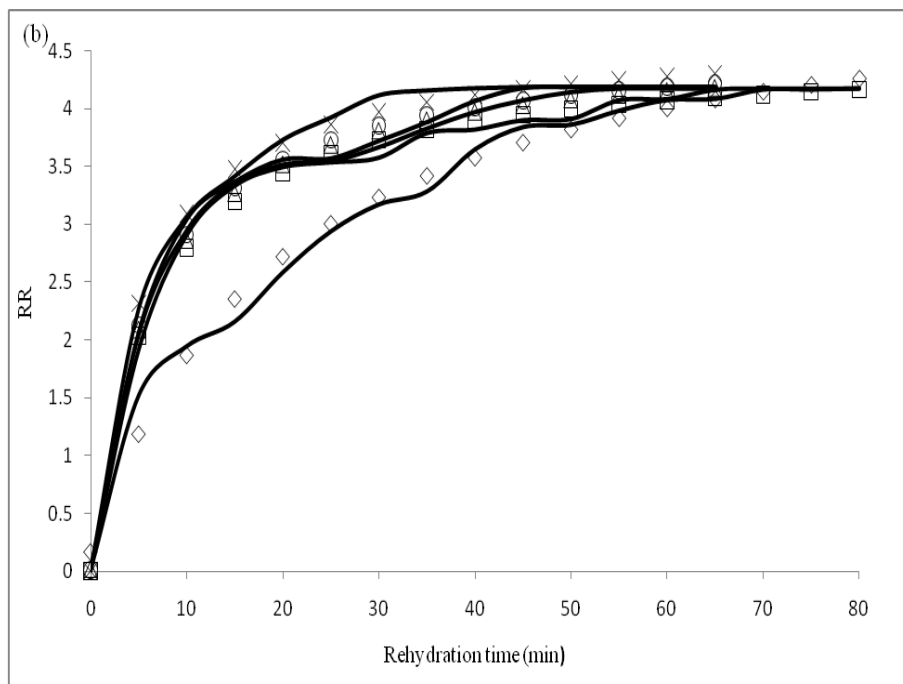
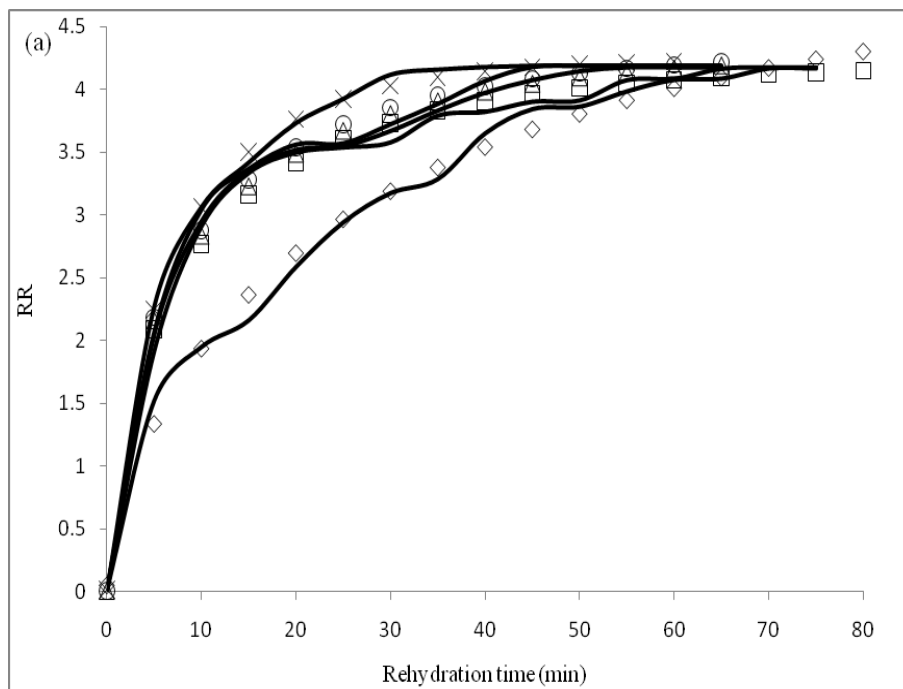


Fig. 2



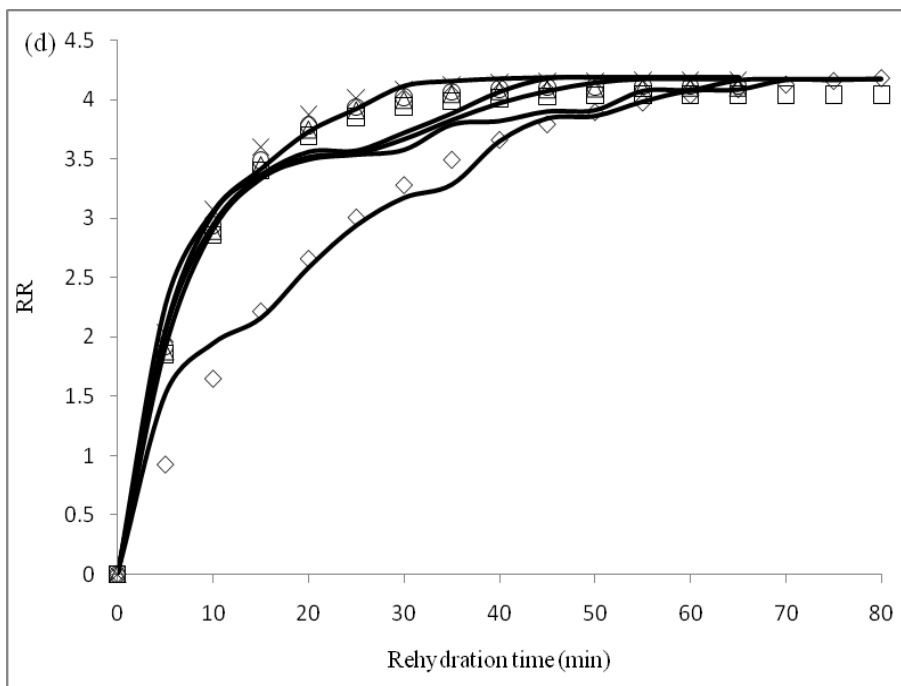
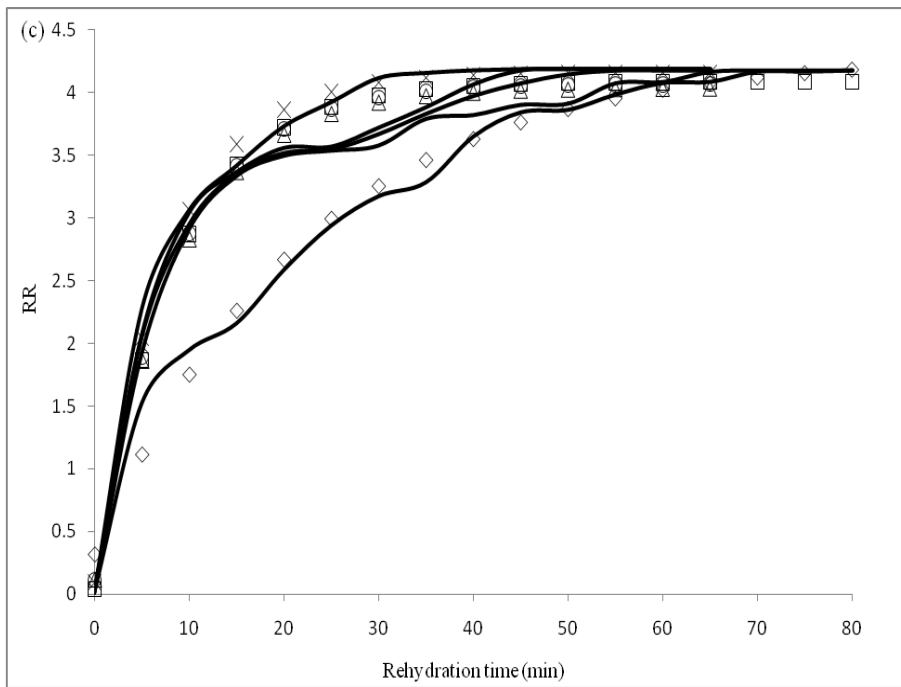
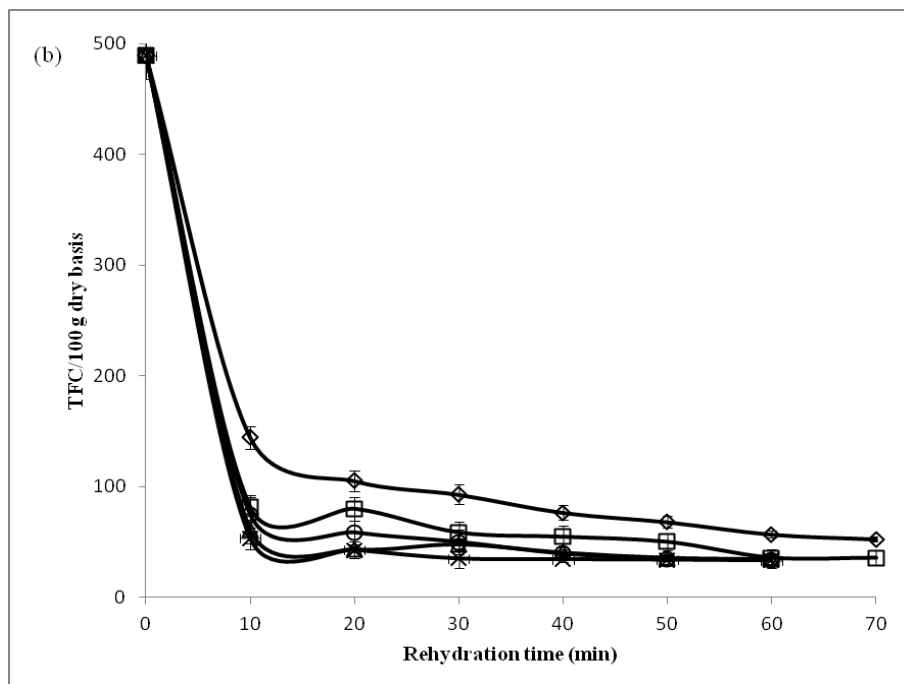
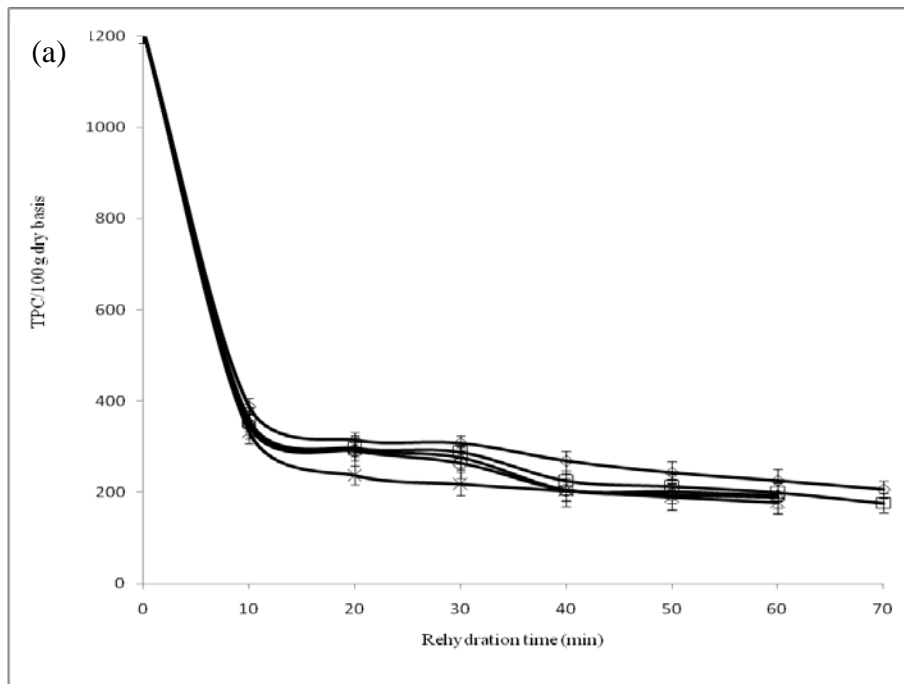


Fig. 3



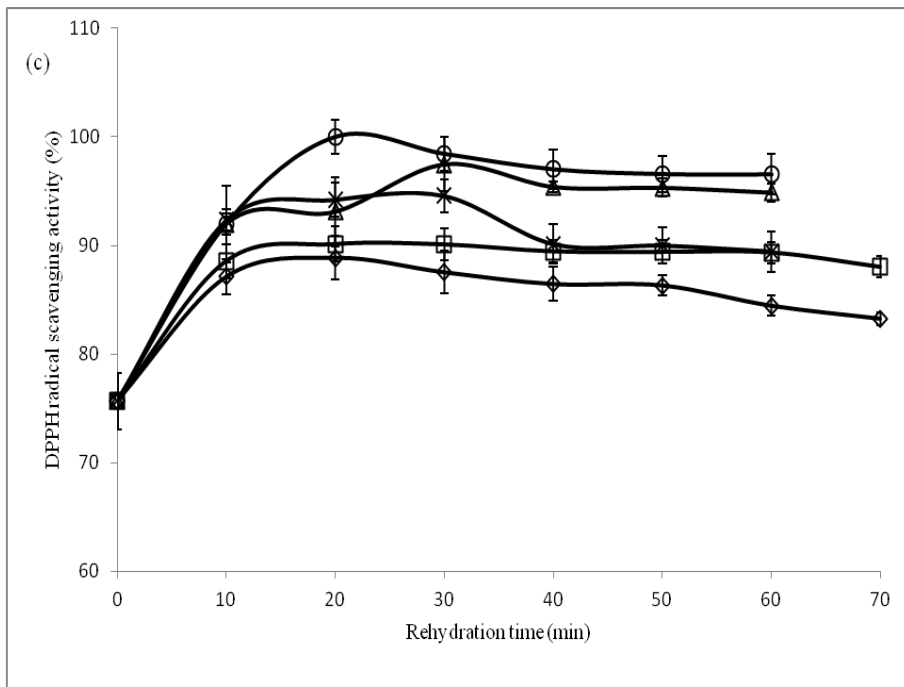


Fig. 4

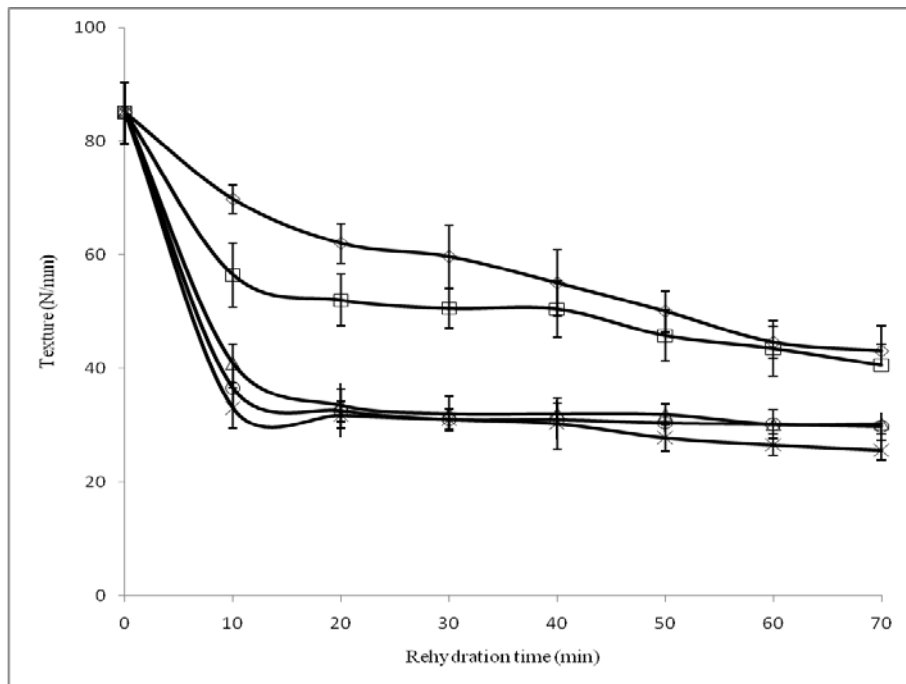


Fig. 5

