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Effect of different drying temperatures on the moisture and phytochemical constituents of edible Irish brown seaweed

Shilpi Gupta, Sabrina Cox, Nissreen Abu-Ghannam*

School of Food Science and Environmental Health, College of Sciences and Health, Dublin Institute of Technology, Cathal Brugha St., Dublin 1, Ireland

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ABSTRACT

The effect of different temperatures on the drying kinetics and the phytochemical constituents of edible Irish brown seaweed, *Himanthalia elongata* were studied. This kinetic study involved the modelling of the terms of Fick's diffusion equation, for estimation of the diffusion coefficients. The diffusivity coefficient increased from 5.6×10^{-07} to 12.2×10^{-07} m^2/s as the drying temperatures increased with an estimated activation energy of 37.2 kJ/mol. The experimental data was also fitted to different empirical kinetic models, Newton, Logarithmic and Henderson–Pabis, and the goodness of fit for the different models was evaluated. The effect of drying temperatures on the phytochemical constituents in seaweed was also evaluated. Drying at 25 °C resulted in 49% and 51% reduction in the total phenol and total flavonoid content, respectively, as compared to fresh seaweed. However, the reduction declined as the drying temperatures were increased. The scavenging effect on DPPH radical was also greater for the fresh seaweed as compared to the dried form. An increase in the phytochemical content was seen for higher temperatures (35 °C and 40 °C) when the moisture content reduced by 50% indicating that this semi-dry state is even more nutritious than the fresh form and could be an interesting starting point for seaweed processing.

1. Introduction

Seaweeds are a part of staple diet in the orient as they are nutritionally rich materials (Dawczynski, Schubert, & Jahreis, 2007); but to a much lesser extent in the rest of the world. Beneficial nutrients in seaweeds include vitamins, trace minerals, lipids, amino acids, and antioxidants, all of which form the part of a healthy diet (Athukorala, Kim, & Jeon, 2006). Numerous studies have reported on the excellent antioxidant capabilities of seaweeds or their extracts (Chandini, Ganesan, & Bhaskar, 2008; Cox, Abu-Ghannam, & Gupta, 2009). They live in a harsh environment where they are exposed to a wide range of environmental stress such as light, rapid fluctuations in temperatures, osmotic stress and desiccation. These factors can lead to the formation of free radicals and other strong oxidising agents but seaweeds seldom suffer any serious photodynamic damage. This fact implies that seaweed cells have some protective mechanisms and compounds (Matsukawa et al., 1997).

Being marine in nature seaweeds contain a large amount of water. When fresh, they have 75–85% water and 15–25% organic components and minerals. Since seaweeds are perishable in their fresh state and could deteriorate within a few days after harvest, drying is an essential step before they can be used in industrial processing. Drying decreases the water activity which ultimately retards the microbial growth, helps to conserve the desirable qualities and reduces the storage volume. However, enzymatic and/or non-enzymatic processes that may occur during drying of the fresh plant tissues may lead to significant changes in the composition of phytochemicals (Capecka, Mareczeek, & Leja, 2005). Studies by Nicoli, Anese, and Parpinel (1999) showed that the overall antioxidant capacity of certain foods may be enhanced due to improvement in the antioxidant properties of naturally occurring antioxidants and the formation of Maillard reaction products (MRPs).

Seaweeds are generally sun dried by spreading them over a net, a tarpaulin or over coconut leaves on the ground. In Ireland, drying of seaweeds for the production of different grades of seaweed meal is carried out in rotary dryers heated by coal slack fired kilns (http://www.cleanerproduction.ie). Different drying methods have been found to greatly affect the nutritional composition of the brown seaweed, *Sargassum hemiphyllum* (Chan, Cheung, & Ang, 1997). Wong and Cheung (2001) reported that oven-drying was better than freeze-drying for the extractability and quality of proteins isolated from three subtropical brown seaweeds.

Presently seaweeds are sold in health shops and oriental grocery houses in the dried form. The dried seaweeds can be used as a part

* Corresponding author. Tel.: +353 1 402 7570; fax: +353 1 878 8978.
E-mail addresses: nissreen.abughannam@dit.ie, shilpi.19may@gmail.com (N. Abu-Ghannam).

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Nomenclature

a, c, k	Parameters in the models
D_{eff}	Effective diffusivity (m^2/s)
D_o	Diffusivity at an infinite temperature (m^2/s)
E_a	Activation energy for moisture diffusion (kJ/mol)
l	Thickness of seaweeds (m)
MR	Moisture ratio
R	Gas law constant (J/molK)
R^2	Coefficient of determination
RMSE	Root mean square error
SSE	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)
χ^2	Chi-square

of a raw vegetable salad, as a natural seasoning or as a snack with fresh juice. Some studies are available in literature which study the effect of drying on the nutritional properties of seaweeds but no literature is available studying the effect of drying on the phytochemical constituents such as phenols and flavonoids.

The moisture removal and its dependence on the process variables are expressed in terms of the drying kinetics, being essential for the development of a reliable process model. Empirical equations frequently used to model the drying kinetics of food include: Newton, Page, Henderson–Pabis, Logarithmic, Diffusion approach and others (Simal, Femenía, Garau, & Roselló, 2005; Vega, Uribe, Lemus, & Miranda, 2007).

The present work aimed to study the drying kinetics of *H. elongata* at a range of temperatures (25, 30, 35 and 40 °C) which are applied in the seaweed industry and to evaluate till what extent drying conditions influence the phytochemical content of the seaweeds. These objectives are justified having in mind that the literature lacks some information on the air-drying kinetics of seaweeds either in terms of empirical models or in terms of diffusivity models. Besides, the change in the phytochemical content due to drying has not been explored.

2. Materials and methods

2.1. Seaweed material

Brown seaweed *H. elongata* was supplied from Quality Sea Veg., Co. Donegal, Ireland. Samples were collected in January 2010, washed thoroughly with freshwater to remove epiphytes and salt and stored at −18 °C until further 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. Sample (5 g) was weighed and placed on a flat tray and dried in a hot air oven (Innova 42, Mason Technology, Ireland) at different temperatures of 25, 30, 35 and 40 °C. The air velocity was set at 2.0 ± 0.1 m/s as measured with digital anemometer (VWR, Ireland). Samples were withdrawn after every hour until 8 h and then after every 8 h for 24 h. 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. Drying kinetics expressed in terms of empirical models

The data obtained experimentally for the four different temperatures studied (25, 30, 35 and 40 °C) was plotted as a dimensionless variable moisture ratio (MR) versus time:

$$MR = \frac{W - W_e}{W_0 - W_e} \quad (1)$$

where W is the moisture content at any time t, W_e the equilibrium moisture content and W_0 is the initial moisture content and all expressed as g water/g dry solids. The experimental data (MR Vs time, t) were fitted to the three different empirical models (Table 1) using STATGRAPHICS Centurion XV (StatPoint Technologies, Inc., Warrenton, VA).

2.4. Estimation of diffusion coefficient

The most widely studied theoretical model in thin layer drying of foods is given by the solution of Fick's second law which was used to fit the experimental drying data. For sufficiently long drying times, the Fick's equation (Coulson, Richardson, Backhurst, & Harker, 1987) can be simplified to Eq. (2):

$$MR = \frac{8}{\pi^2}\left(e^{-D_{eff}t\left(\frac{\pi}{2l}\right)^2}\right) \quad (2)$$

The above equation assumes that the effective diffusivity (D_{eff}) is constant and that shrinkage of the sample is negligible. The above equation can be further simplified into a straight line:

$$\ln(MR) = \ln\frac{8}{\pi^2} - D_{eff}\left(\frac{\pi}{2l}\right)^2 t \quad (3)$$

Slope of the above line will give the value of effective diffusivity at different temperatures as:

$$Slope = -D_{eff}\left(\frac{\pi^2}{4l^2}\right) \quad (4)$$

The effective diffusivity varies with the temperature according to Arrhenius dependence as:

$$D_{eff} = D_0\exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

where D_0 is diffusivity at an infinite temperature (m^2/s), E_a is the activation energy for moisture diffusion (kJ/mol), T is the drying temperature (Kelvin) and R is the gas constant (8.314 J/molK).

Upon linearization, the slope indicates the activation energy:

$$\ln D_{eff} = \ln(D_0) + \left(-\frac{E_a}{R}\right)\frac{1}{T} \quad (6)$$

2.5. Effect of drying on the phytochemical analysis

2.5.1. Preparation of seaweed extracts

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

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

Model name	Equation
Newton	$MR = \exp(-kt)$
Logarithmic	$MR = a\exp(-kt) + c$
Henderson–Pabis	$MR = a\exp(-kt)$