Determination of kelp (*Laminaria digitata*) technological characteristics depending on the drying method

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Abstract. The paper considers four methods of drying kelp (*Laminaria digitata*): convective dehydration at an air temperature of minus 5 ºC, relative air humidity of 55 and 90 %; vacuum drying at a metal carrier temperature of 20 °C and a vacuum depth of 250 Pa; convective dehydration at an air temperature of 20 °C and a relative air humidity of 35 %. In dried algae, the final moisture content, water activity, and strength characteristics were evaluated. To determine the swelling coefficient, dry algae were pre-crushed. It was established that at a temperature of minus 5 °C and a relative air humidity of 90 %, dehydration had an unsatisfactory result in terms of the final moisture content of the finished product 27.4 %. This type of drying at a relative air humidity of 55 % provides a final moisture content of the product (12.3 ± 0.48) % and a relatively high swelling coefficient of 6.9. Algae, dehydrated at minus 5 °C, had elastic properties, in contrast to other considered methods. Vacuum drying made it possible to obtain the minimum final moisture content of dry algae and the highest swelling coefficient of 7.7. However, drying to constant weight lasted 25.5 hours. Of the considered drying options, the convective method (t = 20 °C) showed the highest rate. The duration of drying to constant weight was 8 hours. The final moisture content of the product was acceptable (9.8±1.52) %. However, the water activity after algae swelling had the highest value of 0.97±0.004, and the swelling coefficient had a relatively low value of 6.5. In further studies, it is planned to study the effect of various methods of algae dehydration on the preservation of its biologically active substances.

1 Introduction

An urgent task for the Arctic Basin is the rational use of its resource base, including the processing of seaweed.

Marine vegetation from the class of brown algae is currently a fairly common and promising raw material for extraction, cultivation and processing for food purposes [1-2].

There is a growing consumer interest in health-promoting algae products [3-5]. Algae can be used as the main raw material for food production, as well as various food and biologically active additives in order to impart functional properties to food products.

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Biologically active substances of brown algae are widely used in cosmetology and medicine [6].

Brown algae are an indispensable raw material for the production of alginates, fucoidan, laminaran. Brown algae have a significantly higher content of macro- and microelements compared to other types of algae [6]. Also, brown algae are one of the main sources of iodine, which allows them to be used in certain types of food products, as well as biologically active additives. However, it should be noted that both too low and too high levels of iodine intake can lead to negative consequences for human health [4, 7].

Kelp (*Laminaria digitata*) contains more iodine than other algae [1, 6]. It has been established that blanching and soaking kelp in water at different temperatures significantly reduces the iodine content [4]. For example, blanching in water at a temperature of 45°C and a duration of 120 s reduces the iodine content in kelp by 13 times from the initial value [7-8]. On the other hand, the freezing-thawing process of kelp does not lead to a significant decrease in the iodine content [8].

The most common way to store kelp is its dehydration (drying), however, during drying, the biologically active substances contained in it may be lost. Therefore, in this study, in order to preserve the valuable nutrients of kelp during drying, various methods were used, including low-temperature dehydration modes, for example, at minus 5 °C, which, according to I.N.Tolstorebrov [9], have proven themselves well when drying washed raw materials.

The aim of the study is to determine the technological characteristics of kelp, depending on the method of drying. To achieve this goal, the following research objectives are formulated:

- To determine the initial characteristics of raw materials (initial moisture content, water activity, specific surface area).
- To choose methods of algae dehydration.
- To determine the technological parameters of dried kelp depending on the drying method (final moisture content, water activity, consistency of dried kelp, swelling coefficient, moisture content after swelling).
- To prove the technological modes of kelp dehydration, depending on the final characteristics of the product.

2 Materials and methods

The research was carried out at the department of food production technologies and in the educational and experimental workshop of the university. The raw material used was frozen kelp (*Laminaria digitata*), harvested on the coast of the Barents Sea in September 2022.

Humidity w (%) of raw materials and dehydrated kelp was determined by the gravimetric method using an Evlas-2M moisture analyzer.

Water activity A_w was determined on a Rotronic device (Denmark).

The specific surface S/m of algae was determined by calculation as the ratio of the area S of the sample to its mass m.

Algae drying was carried out on a small-sized drying plant (SSDP) designed and manufactured by MSTU specialists, in a VTC-K52-250 vacuum drying cabinet, and in Minicella MM and CRYSPI medium-temperature refrigerators.

The vacuum depth P was determined using a VSP63DL vacuum sensor with a Thyracont VD12 control and indication unit (Germany).

The temperature t and relative air humidity φ in the cooling and drying chambers were controlled using a CENTER 311 thermohygrometer (Taiwan).

The flow velocity v in the chambers was determined using an RGK AM-30 digital anemometer (China).

The rate of dehydration V_{100} (%/h) to 100% moisture on dry weight was calculated using the formula:

$$V_{100} = (w^c{}_0 - 100)/\tau, \tag{1}$$

Where $w^c{}_0$ is the initial moisture content of algae on a dry basis, %; τ - time to reach 100% moisture content on dry weight, h.

The strength of the dried samples was evaluated using a Food Texture Analyzer FRTS-11 (Japan).

Grinding of dry algae was carried out on a laboratory mill with a cooling function LM 202 (Russia).

The granulometric composition of dehydrated dry algae was determined using a set of metal sieves (Russia).

The swelling coefficient was determined as the ratio of the product mass before and after its recovery.

3 Results

The algae were thawed in air, washed with water, and left to drain in perforated containers.

Studies of raw material (thawed kelp) found that:

- Initial humidity of kelp is w_0 = 77.1 % ± 0.9 %.
- Kelp water activity is A_w = 0.95±0.02.
- Specific surface area S/m of kelp is 2.6 m^2/kg ± 0.6 m^2/kg.

3.1 Drying algae

Thawed algae were dried by four methods.

Method 1 - convective dehydration in a CRYSPI chamber: air temperature is minus 5 ºC; relative air humidity is 55 %; flow velocity is v 0.2-0.5 m/s; the air movement mode is periodic.

Method 2 - convective dehydration in the Minicella MM chamber: temperature is minus 5 °C, relative air humidity is 90 %; flow rate is 0.3 - 0.6 m/s; air movement mode is constant.

Method 3 - vacuum drying in the vacuum drying cabinet VTSh-K52-250: temperature of metal carriers is 20 °C; vacuum depth is 250 Pa.

Method 4 - convective dehydration in SSDP: air temperature is 20 °C; relative air humidity is 35 %; flow rate is 1.0-1.5 m/s.

Figure 1 shows the algae dehydration kinetics curves obtained during the experiments, which clearly indicate that the process of convective drying at 20 °C proceeds at the highest speed.

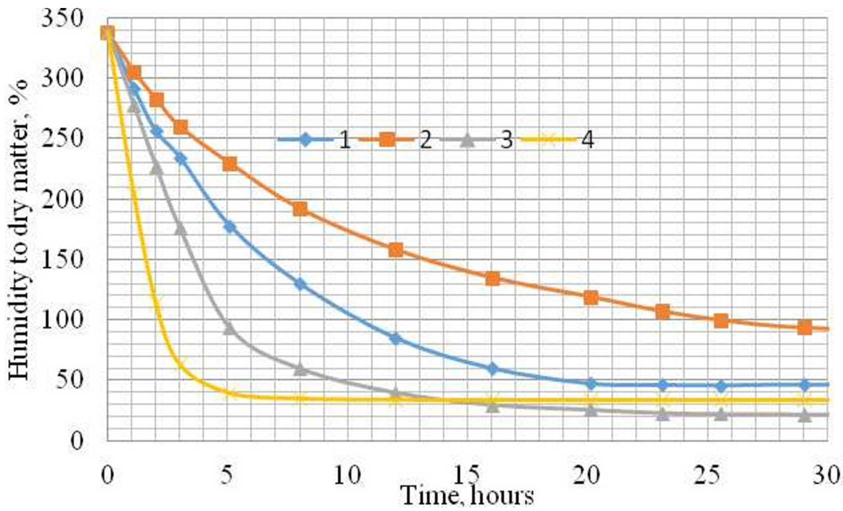


Fig. 1. Algae dehydration kinetics: 1 - convective dehydration: t = - 5 °C; φ = 55 %; 2 - convective dehydration: t = - 5 °C; φ = 90 %; 3 – vacuum drying: t = 20 °C; P = 250 Pa; 4 - convective dehydration: t = 20 °C; φ = 35 %.

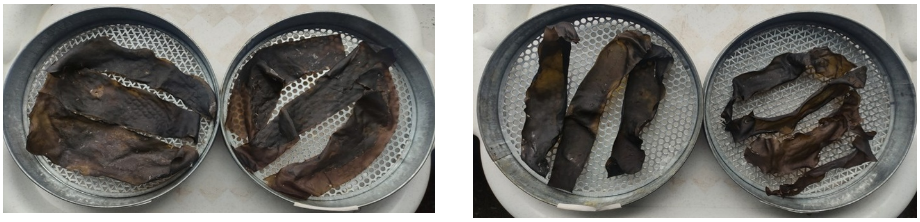
The results of studies of the final moisture content and water activity of dried kelp, depending on the selected dehydration methods, are presented in Table 1.

Table 1. Physical and chemical parameters of dried kelp.

Dehydration method	Characteristics of dry kelp		
	Final moisture $w_к$, %	Water activity A_w	Algae consistency
Convective dehydration: t = - 5 °C; φ = 55 %.	12.3±0.48	0.42±0.001	elastic
Convective dehydration: t = - 5 °C; φ = 90 %.	27.4±1.37	0.77±0.009	-
Vacuum drying: t = 20 °C; P = 250 Pa	8.5±0.42	0.28±0.006	tough
Convective dehydration: t = 20 °C; φ = 35 %.	9.8±1.52	0.38±0.002	tough

Figure 2 shows kelp plates before dehydration, placed on perforated metal carriers.
Figure 3 shows kelp plates after dehydration.

Fig. 2 Kelp (*Laminaria digitata*) samples on perforated carriers before processing.



a b c d

Fig. 3. Laminaria plates after dehydration: a - convective dehydration: : t = - 5 °C, φ = 55 %; b - convective dehydration t = - 5 °C, φ = 90 %; c – vacuum drying: : t = 20 °C, P = 250 Pa; d - convective dehydration: : t = 20 °C, φ = 35 %.

3.2 Study of the samples strength characteristics

Samples of dried kelp were sent for evaluating their strength characteristics using the Food Texture Analyzer FRTS-11. In this case, a metal spherical indenter with a diameter of 20 mm was used as a working body. Immersion of the indenter was carried out until the sample is deformed, or up to the maximum possible penetration depth L, equal to 10 mm. The strength Str (N·mm) of the sample was calculated as the product of the impact force F (N) and the penetration depth of the indenter (mm). Kelp samles obtained using method 2 were not used in the strength assessment, because these samples had significant plasticity due to the high content of the final moisture $w_{\text{к}}$ = 27.4 %. Data on the study of the strength characteristics of kelp dried samples are presented in Table 2.

Table 2. Data on the strength characteristics of kelp dried samples.

Drying parameters at which the sample was obtained	Strength Str (N·mm)	Condition of samples after physical impact
Method 1 - convective dehydration: t = - 5 °C, φ = 55 %	960.0	the samples were not destroyed, after physical impact they took on their original shape
Method 3 - vacuum drying: t = 20 °C, P = 250 Pa	27.5	samples were destroyed
Method 4 - convective dehydration: t = 20 °C, φ = 35 %	67.7	samples were destroyed

3.3 Study of the dried samples swelling

To evaluate the obtained samples of dried kelp, their swelling in water was studied. Previously, dry algae were crushed, because. in this state, dry algae are better packaged, take up less usable space during storage, and it is more convenient to use a dry finely ground product during further processing. The results of granulometric analysis are presented in Table 3.

Kelp recovery was carried out at a ratio of dry crushed algae and water of 1:10. The holding time for swelling is 2 hours, the water temperature is 20 °C. After exposure, the algae were placed on perforated surfaces to drain excess water. Characteristics of kelp after recovery is presented in Table 4.

Table 3. Results of granulometric analysis of dry crushed algae.

Fraction size, mm	Fraction quantity, %
from 2.50 to 1.25	15.0
from 1.25 to 0.630	47.7
from 0.63 to 0.315	23.2
from 0.315 to 0.160	9.3
less 0.160	3.8

Table 4. Characteristics of kelp after recovery.

Drying parameters at which the sample was obtained	Swelling coefficient	Kelp humidity after recovery, %	Water activity A_w after kelp recovery
Convective dehydration: t = - 5 °C, φ = 55 %	6.9	88.0±0.6	0.95±0.01
Convective dehydration: t = - 5 °C, φ = 90 %	6.3	87.3±0.9	0.96±0.001
Vacuum drying: t =20 °C, P = 250 Pa	7.7	87.6±0.8	0.96±0.002
Convective dehydration: t = 20 °C, φ = 35 %	6.5	86.7±0.9	0.97±0.004

4 Discussion

The curves of the algae dehydration kinetics obtained during the experiments (Figure 1), which clearly indicate that the process of convective drying at 20 °C proceeds at the highest speed (method 4). The dehydration rate V_{100} for this method was 103.6 %/hour. Next in intensity is the average rate for vacuum drying (method 3) - 50.7 %/hour. For drying methods 1 and 2, the average dehydration rate was 22.7 %/hour and 9.5 %/hour, respectively.

The minimum moisture content of dry algae was observed in samples obtained by vacuum drying. For convective drying at a temperature of 20 °C, the maximum rate of dehydration was observed, but the final moisture content of algae was higher than that of products obtained using vacuum drying. Convective dehydration at a temperature of minus 5 °C and a relative air humidity of 90 % showed an unsatisfactory result in terms of the final moisture content of the finished product $w_к$ = 27.4 %. According to the regulatory documentation, the final humidity of kelp should be no more than 15 % [10].

Based on the data in Table 2, it can be seen that the samples of convective dehydration (t = - 5 °C, φ = 55 %) had elastic properties and did not collapse under the influence of a spherical indenter even at its maximum penetration depth. The samples of vacuum drying turned out to be the least strong, the strength of which was 27.5 N·mm. The strength of samples of convective drying (t = 20 °C, φ = 35 %) was 67.7 N·mm, which indicates their higher strength relative to samples of vacuum drying.

The results obtained made it possible to recommend the convective dehydration method at minus 5 °C for kelp drying, which is supposed to be used in products not requiring additional recovery.

The studies results of the dehydrated kelp swelling have established that, under equal conditions, the algae dried by the vacuum method, the swelling coefficient of which is 7.7, is best recovered. The use of this method implies the highest yield of recovered kelp, which is the preferred technological characteristic in the products manufacture.

The humidity of the restored kelp differed slightly for the considered drying methods and averaged (87.4 ± 0.8) %. This value exceeds the initial humidity of kelp (77.1±0.9) %.

The increase in the kelp moisture content is due to the fact that dry crushed algae were used for recovery, which have a significantly larger specific surface area than the non-crushed object. The water activity of the recovered algae is close to the water activity of the kelp before drying.

5 Conclusion

Of the considered drying options, the convective method (t = 20 °C) showed the highest rate. The duration of drying to constant weight was 8 hours. The final moisture content of the product was acceptable (9.8±1.52) %. However, water activity after algae swelling had the highest value - 0.97±0.004. Swelling coefficient was 6.5. This is the minimum value of the swelling coefficient among the considered drying methods, which had a satisfactory result. This method is close to drying algae in natural conditions.

Vacuum drying made it possible to obtain the minimum final moisture content of dry algae and the highest swelling coefficient of 7.7. However, drying to constant weight lasted 25.5 hours.

Convective dehydration at minus 5 ^{0}C and a high relative humidity of 90 % had an unsatisfactory result in terms of final product moisture. This type of drying at a relative air humidity of 55 % gives better results: the final moisture content of the product is 12.3 % ± 0.48 %, the swelling coefficient is 6.9. The algae dried by this method had elastic properties. To optimize this method, it is planned to reduce the air relative humidity and increase the rate of its circulation in the drying chamber.

Research is expected to continue in the direction of studying the effect of various methods of dehydration of algae on the preservation of its biologically active substances, in particular, iodine.

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