

Review

The Effect of Pre-Treatment and the Drying Method on the Nutritional and Bioactive Composition of Sea Cucumbers—A Review

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Abstract: Sea cucumbers are well demarcated for their valuable role in the food, pharmaceutical, nutraceutical, and cosmeceutical sectors. The demand for well-processed dried sea cucumber retaining quality is prioritized by local markets and industries. There are several techniques for the pre-processing of fresh sea cucumbers, including traditional and modern methods, such as salting, boiling, high-pressure processing, high-pressure steaming, and vacuum cooking, among others, in order to inactivate enzymes and microbial attacks. Further, pre-treated sea cucumbers require post-processing before human consumption, transportation, or industry uses such as hot air, freeze, cabinet, sun, or smoke drying. However, despite the ease, traditional processing is associated with several challenges hampering the quality of processed products. For instance, due to high temperatures in boiling and drying, there is a higher chance of disrupting valuable nutrients, resulting in low-quality products. Therefore, the integration of traditional and modern methods is a crucial approach to optimizing sea cucumber processing to obtain valuable products with high nutritional values and retain bioactive compounds. The value of dried sea cucumbers relies not only on species and nutritional value but also on the processing methods in terms of retaining sensory attributes, including colour, appearance, texture, taste, and odour. Therefore, this review, for the first time, provides insight into different pre- and post-treatments, their perspective, challenges, and how these methods can be optimized for industry use to obtain better-quality products and achieve economic gains from sea cucumber.

Keywords: sea cucumber; pre-treatment; post-processing; chemical composition; nutraceutical and pharmaceutical value



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1. Introduction

Sea cucumbers are the marine invertebrates of the *Holothuroidea* class, distributed worldwide and living on the surface of the ocean in warm shallow waters, near corals, seaweeds, or rocks [1–3]. Approximately 1500 varieties of sea cucumbers are reported to be found worldwide; however, about 100 species are used for food/ medicinal purposes [2]. Sea cucumbers contain more than 50 types of biomolecules, including proteins (amino acids, collagen, and peptides), lipids (polyunsaturated fatty acids), sulphated polysaccharides (fucosylated chondroitin sulphate and fucoidan), ash, lectins, saponins, glycosides, phenolics (phenolic acids and flavonoids), and sterols, which are well reported for their anti-cancer, anti-tumour, anti-coagulation, antioxidant, antidiabetic, antihypertensive, antiglycation, and anti-osteoclastogenesis properties [1,4–9]. For instance, sea cucumber processing discards, mainly internal organs along with or without tentacles/aquapharyngeal bulbs/flowers, are rich sources of essential amino acids, polyunsaturated fatty acids, and phenolic compounds, which exhibit potent antioxidant activity [4,6,10].

Not only the chemical composition but also the processing of sea cucumbers varies depending on the country of origin, species, and available technologies. For example, Malaysia, the Philippines, China, Madagascar, and some areas of the Pacific use different techniques for sea cucumber processing. However, sea cucumber processing generally includes four stages, namely weeding, boiling, salting, and drying, as shown in Figure 1 [9,11–13], which possess a positive impact on the product quality [14]. For instance, textural damages, including the denaturation, degradation, and aggregation of proteins, can take place during the processing and storage of sea cucumbers [15]. Their visualization, such as appearance, texture, odour, fungal infection, and proximate composition, including protein, ash, and water contents, are the major parameters to determine the quality of sea cucumbers [9]. The traditional processing reported in Figure 1 with boiling and sun drying often leads to reducing the overall quality of sea cucumbers [12,14], thereby affecting their selling price both locally and internationally [16]. In addition, different species of sea cucumbers require different processing techniques to gain quality products, including the shape of sea cucumbers. The overall quality mainly depends on the thickness and texture of the body wall (a major marketable body part) of sea cucumbers, along with the water-holding capacity after boiling [11]. For example, the body wall and skin of *Bohadschia vitiensis* (0.7 cm), *B. similis* (0.4 cm), *Holothuria edulis* (0.3 cm), and *Actinopyga miliaris* (0.9 cm) are soft [17–20]. Therefore, boiling should be avoided as it can damage the body wall (e.g., hampering the body wall composition), and, hence, salting is required before drying to remove water and inactive microorganisms from the body wall [21]. However, in the case of sea cucumbers such as *Thelenota ananas* and *Stichopus vastus*, with thick and tough body walls, repeated boiling and drying are needed, which are enough to render the microorganisms inactive; therefore, salting is not required before boiling [21]. On the other hand, the outer skin layer of *Holothuria scabra* must be removed before boiling because the skin is thick, tough, and chalky [21].

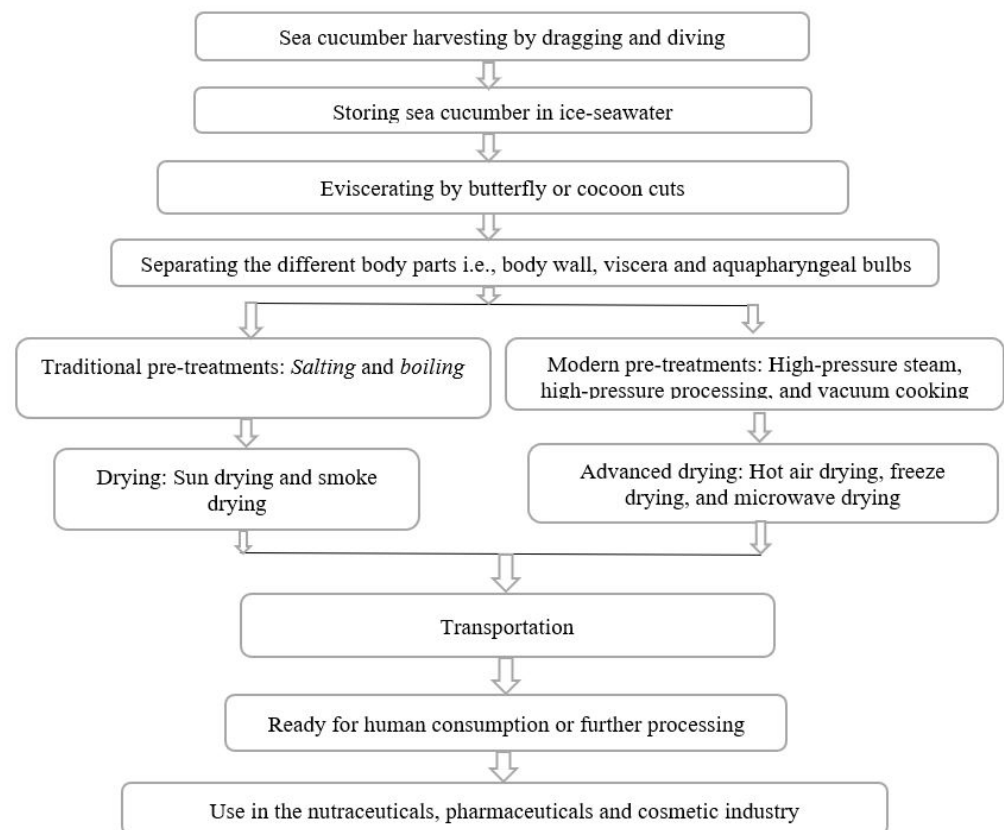


Figure 1. Flow diagram of sea cucumber processing: traditional vs. modern.

After harvesting sea cucumbers, hydrolysis starts within a few hours, and due to this, storage and transportation become complex because of quality degradation [22]. Hence, pre-cooking procedures are used in fresh or raw sea cucumbers as they help to prevent auto-enzymatic reactions [22]. After that, pre-cooked sea cucumbers are frozen for storage and kept for further processing [22]. Pre-treatments such as boiling, salting, smoking, drying, or freezing sea cucumbers are essential to produce good-quality products [23]. Moreover, boiling temperature, time, and pressure are related to maintaining the quality of boiled sea cucumber [15]. The shelf life and storage capability of the products are greatly affected by the processing methods. After processing, sea cucumbers can be marketed in three product forms: dried, pickled, and ready-to-eat [15]. However, consumers' choices can be altered upon the loss of nutrients and changes in the shape and texture of the products [24].

To date, the traditional and conventional methods (Figure 1) are widely used to process sea cucumbers worldwide; however, new processing technologies, including high-pressure steaming [25], low-temperature treatment [26], far-infrared radiation drying [27], the generation of the 3D-printed recombinant product [28], and freeze drying [29], have been incorporated in recent years for improving the texture and sensory appearance of sea cucumber products. Therefore, this review aims to provide insight into different sea cucumber processing methods and the impact of integrated approaches in obtaining better nutritional and bioactive compositions. To the best of our knowledge, this is the first review article where the effects of different pre-treatment (e.g., boiling, blanching, steaming, pressurizing, and heating) and drying (e.g., hot air, freeze, and microwave drying) methods on the biochemical and physicochemical composition of sea cucumbers are compiled.

2. Proximate Composition of Sea Cucumber

It has been reported that the proximate composition, such as moisture, protein, ash, and lipid content, in sea cucumbers varies greatly from species to species (Table 1). For instance, *Holothuria atra* could be a good source of protein over 80% [30] while *Cucumaria frondosa* represented a great source of lipids (26.12%) on a dry basis [1]. In addition, Table 2 shows that sea cucumbers also contain minerals, including mean calcium (3918.84 mg/g), sodium (5935.39 mg/100 g), magnesium (1377.85 mg/100 g), potassium (505.54 mg/100 g), and many more, which is a crucial part of the important enzymes, and they are involved in various roles as catalysts and antioxidants [31–37]. Mineral content also varies from species to species, and it was observed that *Holothuria tubulosa* and *Apostichopus japonicus* could be good sources of minerals [33,37].

Table 1. Proximate composition of different species of sea cucumbers.

Species	Moisture (%)	Ash (%)	Protein (%)	Lipid (%)	References
<i>Bohadschia vitiensis</i> (DB)	-	30.78	17.69	-	[9]
<i>Apostichopus japonicus</i> Selenka (DB)	5.10	34.90	52	5.11	[37]
<i>Cucumaria frondosa</i> Viscera (DB)	-	11.95	48.26	26.12	[1]
<i>Stichopus japonicus</i> (DB)	-	34.15	52.4	12.4	[38]
<i>Holothuria lessona</i> (DB)	13.47	34.51	41.18	3.02	[39]
<i>Holothuria atra</i> (DB)	4.5	7.3	82.9	2.4	[30]
<i>Stichopus herrmanni</i> (DB)	10.2	37.9	47.0	0.8	[40]
<i>Thelenota ananas</i> (DB)	15.1	25.1	55.2	1.9	[40]
<i>Thelenota anax</i> (DB)	1.2	39.2	40.7	9.9	[40]
<i>Holothuria fuscogilva</i> (DB)	11.6	26.4	57.8	0.3	[40]
<i>Holothuria fuscopunctata</i> (DB)	7.0	39.6	50.1	0.3	[40]
<i>Actinopyga mauritiana</i> (DB)	11.6	15.4	63.3	1.4	[40]
<i>Actinopyga caerulea</i> (DB)	0.81	28.4	56.9	10.1	[40]
<i>Bohadschia argus</i> (DB)	13.0	17.7	62.1	1.1	[40]
<i>Actinopyga echinites</i> (DB)	9.30	29.25	60.20	1.25	[41]
<i>Parastichopus californicus</i> (DB)	4.03	25.73	47.03	8.19	[30]
<i>Stichopus chloronotus</i> (DB)	-	27.7	57.93	3.94	[42]

Table 1. Cont.

Species	Moisture (%)	Ash (%)	Protein (%)	Lipid (%)	References
<i>Holothuria spinifera</i> (DB)	-	48.14	47.16	1.03	[42]
<i>Apostichopus japonicus</i> (WB)	91.71	2.97	3.35	0.29	[37]
<i>Holothuria tubulosa</i> (WB)	84.04	6.63	10.33	0.20	[3]
<i>Cucumaria frondosa</i> Viscera (WB)	82.07	2.14	8.65	4.68	[1]
<i>Isostichopus</i> sp. aff <i>badionotus</i> (WB)	93.26	3.97	7.21	0.07	[43]
<i>Cucumaria frondosa</i> (WB)	90.5	3.5	5.5	0.8	[44]
<i>Holothuria scabra</i> (WB)	87.12	6.82	5.10	0.37	[31]
<i>Holothuria mammata</i> (WB)	85.24	5.13	11.1	0.55	[45]
<i>Holothuria polii</i> (WB)	81.24	7.85	8.66	0.33	[45]
<i>Stichopus horrens</i> (WB)	92.83	3.4	3.63	0.42	[35]
<i>Holothuria Arenicola</i> (WB)	93.02	2.01	4.47	0.65	[35]
<i>Actinopyga mauritiana</i> (WB)	84.71	2.12	7.00	4.99	[46]
<i>Bohadschia marmorata</i> (WB)	83.17	6.03	6.96	4.83	[46]
<i>Holothuria leucospilota</i> (WB)	81.41	4.3	7.02	4.60	[46]

DB = Dry Basis; WB = Wet Basis.

Table 2. Minerals (mg/100 g dried sample) of the body wall of sea cucumbers.

Species	Cr	Ni	Mn	Cu	Pb	Cd	Zn	Fe	Na	K	Ca	Mg	References
<i>Holothuria Arenicola</i>	-	0.19	5.23	0.95	-	-	4.28	-	4750	520	5700	4750	[32]
<i>Actinopyga mauritiana</i>	-	0.25	5.85	5.11	-	-	5.23	-	6220	620	2610	1870	[32]
<i>Holothuria mammata</i>	0.09	0.05	0.45	-	-	-	1.05	3.37	6650	386	4110	1270	[33]
<i>Holothuria polii</i>	0.08	-	4.62	-	0.31	0.009	0.89	4.06	5690	327	14,500	2140	[33]
<i>Holothuria tubulosa</i>	1.52	0.25	8.66	-	0.65	-	22.77	440	7520	558	9580	1660	[33]
<i>Parastichopus californicus</i>	0.67	0.4	4.36	0.35	-	-	4.04	18.42	8800	400	2500	1400	[34]
<i>Stichopus horrens</i>	-	-	-	-	-	-	0.096	521.78	-	-	106.3	92.5	[35]
<i>Holothuria sanctori</i>	-	-	-	-	-	-	-	-	552.4	-	656.7	155.77	[36]
<i>Holothuria scabra</i>	-	-	-	-	-	-	-	2.84	666.2	61.42	1812.32	304.61	[31]
<i>Apostichopus japonicus</i>	0.67	-	0.65	1.14	-	-	5.02	26.54	18,271.3	1660.15	1506.92	1480.44	[37]
<i>Apostichopus japonicus selenka</i>	0.20	-	0.19	0.85	-	-	0.97	4.12	234	20	25	33	[37]

3. Major Pre-Treatments for Sea Cucumber Processing

Hydrolysis starts within a few hours of harvesting sea cucumbers due to enzymatic activity, transportation duration, and storage complexity [18]. Even though fresh sea cucumbers can be consumed easily with better taste and texture, the problem is sea cucumbers are mainly consumed in East Asian countries, and, therefore, they should be processed in a way that is easy to transport and can extend the shelf life while maintaining overall qualities [37]. Thus, there are several pre-treatments usually conducted in sea cucumber processing, including boiling, salting, drying, and soaking, to obtain quality products. These processing methods are essential for the storage and transport of most sea cucumbers as well as maintaining quality [37]. For these reasons, different types of pre-treatments are followed to inactivate the autolytic enzymatic reaction and retain the proper shape of fresh sea cucumbers immediately after harvesting or collection [15,47]. The body wall of sea cucumbers can be directly consumed after traditional boiling and rehydration. In addition, other modern processing techniques, such as high-pressure steaming [24] and high-pressure processing [7] are used in the industry to increase working efficiency, which greatly affects the sensory characteristics and storage stability of sea cucumbers. The traditional and modern pre-treatments generally used by the local farmers and industries, respectively, are briefly stated below.

3.1. Boiling/Heating

Boiling is required to inactivate microorganisms or reduce microbial decomposition to obtain a quality dried product from sea cucumbers [9]. According to the thickness and texture of the body wall of different sea cucumber species, boiling period and temperature vary greatly. Sea cucumber species with a thin body wall (0.7 cm), such as *Bohadschia vitiensis*, require 5 to 10 min of treatment at 50 to 90 °C. Due to boiling, the texture and appearance of sea cucumbers become elastic and cylindrical [23]. Extreme or very high temperatures should be avoided for boiling because it causes damage to the skin and decreases the appearance of sea cucumbers [48]. Moreover, in industry, sea cucumbers are boiled in hot water to inactivate endogenous enzymes to control proteolysis, including muscle tissue (myofibrillar protein), connective tissue (collagen), and sarcoplasmic protein [24,49,50]. Boiling time is correlated to boiling pressure and temperature; therefore, an appropriate boiling time is required to degenerate the muscle tissues to make them soft [29,48,51]. Due to the prolonged boiling time, the physical properties of the body wall of sea cucumbers, such as hardness, springiness, chewiness, cohesiveness, and resilience, can be significantly decreased, but adhesiveness could be increased (Table 3). Further, these textural properties are strongly related to a sea cucumber's collagen fibre [52].

A sea cucumber's body wall contains collagen, which is highly thermolabile; therefore, adequate time and temperature should be considered during boiling pre-treatment. Boiling has been reported to dramatically affect the structure and composition of collagen in sea cucumbers [53–55]. Wang et al. [56] reported that the collagen fibres of sea cucumber body walls are rearranged and gelation happens under the temperature of 100 °C. Nonetheless, when the temperature exceeds 100 °C, the chemical bonds within the collagen fibres are broken, and the decomposition of collagen fibres starts and causes texture deterioration [57]. Ram et al. [23] stated that 69.81% of collagen was decreased at 80–90 °C of boiling in *Holothuria scabra* (Table 4). Even some physiochemical properties, including water-holding capacity, protein degradation, oxidation, and sensory properties, deteriorate simultaneously with high temperatures over 100 °C [49]. However, Zhang et al. [58] reported that the protein content and cooking yield were increased by 78.5 and 70.3%, respectively, when sea cucumbers were boiled at 100 °C for 45 min as a pre-treatment over the control. Moreover, Table 4 shows that the body wall of *Apostichopus japonicus* was boiled at 100 °C for 10 min, and the saponin content was decreased by 41% over the control [47].

Hence, boiling is traditionally and commercially considered one of the most important pre-treatments for sea cucumber processing. However, boiling at an appropriate temperature and duration should be conducted to maintain physicochemical and nutritional characteristics.

Heating is a crucial stage of sea cucumber processing because it deactivates the autolytic enzymes. In the meat industry, the texture of the meat becomes harder, along with the reduction in water-holding capacity, degradation of protein extractability, and protein solubility due to overheating [59]. Therefore, to improve the eating quality of meat, such as maintaining good muscle, texture, and colour, low-temperature heating is required [57]. The textural quality of the sea cucumber body wall is altered under different heat treatments. Collagen fibres are rearranged under 100 °C, then textural properties deteriorate above 100 °C due to the lower moisture content. Table 3 shows an enhanced hardness and chewiness under 100 °C while springiness, resilience, and cohesiveness are increased above 100 °C [57]. Due to the low heating, the meat becomes tender because of the action of proteolytic enzymes, reduction in fibrils, and solubilization of collagen [8]. Cathepsin L is a lysosomal protease, and one kind of endopeptidase, as well as other proteolytic enzymes, becomes activated during the autolysis of sea cucumbers below 80 °C while these enzymes become deactivated above this temperature [8]. Therefore, boiling time and temperature are crucial factors for retaining the chemical composition of the sea cucumbers, but it relies on the body wall thickness as well as softness.

Table 3. Effect of various processing methods on the texture of sea cucumbers.

Species	Pre-Treatment	Texture						References
		Hardness/g	Adhesiveness	Springiness	Cohesiveness	Chewiness/g	Resilience	
<i>Cucumaria frondosa</i>	Blanch at 40 °C, 60 °C, and 80 °C for 45 min	5955.04–12,532.65	(−668.44)–(−30)	0.54–0.86	0.28–0.78	2020.45–4453.01	0.15–0.44	[58]
	Boiling at 100 °C for 15, 30, 45, 60, and 120 min	3693.17–6504.57	(−41.72)–(−27.89)	0.84–0.90	0.81–0.83	2788.71–4176.96	0.47–0.55	
	Steaming at 100 °C for 15, 30, 45, 60, and 120 min	3090.1–5162.88	(−72.37)–(−20.27)	0.86–0.89	0.77–0.82	2260.60–3415.58	0.43–0.52	
<i>Stichopus japonicus</i>	Heat at 40 °C for 0, 15, 30, 60, 90, and 120 min	15,825.2–37,173.3	NA	0.48–0.71	0.31–0.43	2933.11–10,655.06	0.32–0.41	[8]
<i>Stichopus japonicus</i>	Boiling at 100 °C for 30, 60, 90, 120, 150, and 180 min	552.26–2837.57		0.99–1.68	376.3–4700.2	0.69–0.90	0.64–0.77	[26]
<i>Apostichopus japonicus</i>	Heat at 80 °C for 10, 20, 40, and 80 min	121–948		0.78–0.95	0.59–0.84	111.43–410.87	0.39–0.65	[57]
	Heat at 90 °C for 10, 20, 40, and 80 min	356.5–570.6		0.82–0.97	0.70–0.84	257.75–458.64	0.50–0.63	
	Heat at 100 °C for 10, 20, 40, and 80 min	96–266		0.89–0.96	0.78–0.89	81.60–177.13	0.57–0.71	
	Heat at 110 °C for 10, 20, 40, and 80 min	16.2–303.5		0.42–1.00	0.25–0.90	0.97–257.65	0.44–0.73	
	Heat at 120 °C for 10, 20, 40, and 80 min	27.6–298		0.64–0.94	0.23–0.86	3.43–151.87	0.31–0.68	
<i>Apostichopus japonicus</i>	Heat steam sterilization at 121 °C for 15 min under 0.15 MPa then store for 0, 15, 30, 45, 60, 75, 90, and 160 days	15.67–295.85		0.68–1.03	0.35–0.76	9.18–236.11	0.31–0.54	[53]

Table 4. Different pre-treatments on the proximate and bioactive compounds of sea cucumbers.

Species	Pre-Treatments	Proximate Compounds			Bioactive Compounds				Ref.
		Protein	Lipid	Carb.	Phenolics	Saponin	Polysac.	Collagen	
<i>Cucumaria frondosa</i> (BW)	Boiling at 100 °C for 30 min vs. steaming	11.8% I	-	-	-	-	-	-	[58]
<i>Apostichopus japonicus</i> (BW)	Boiling at 100 °C for 10 min, then vacuum cooking at 95 °C −0.04 MPa for 4 hr	9.95% I	0.59% I	1.64% I	-	-	1.5% I	-	[37]
<i>Stichopus japonicus</i> (BW)	Infrared radiation (10,000 W/m ²) with FD	51.8% I	-	-	-	0.07% I	6.25% I	-	[60]
<i>Apostichopus japonicus</i> (BW)	Boiling at 100 °C for 10 min	11.5% D	-	33% D	-	41% D	-	-	[47]
<i>Cucumaria frondosa</i> (IO)	HPP (200, 400, and 600 MPa for 5, 10, and 15 min)	-	-	-	32.59% I	-	-	-	[7]
<i>Cucumaria frondosa</i> (BW)	HPP (200, 400, and 600 MPa for 5, 10, and 15 min)				29.21% I				[7]
<i>Cucumaria frondosa</i> Flower	HPP (600 MPa for 10 min)				241.38 mg GAE/100 g				[61]
<i>Holothuria scabra</i> (BW)	Brining with 15 g/100 mL of saline	-	-	-	-	-	-	14.28% D	[23]
<i>Holothuria scabra</i> (BW)	Kenching for 24 h	-	-	-	-	-	-	18.49% D	[23]
<i>Holothuria scabra</i> (BW)	Smoking	-	-	-	-	-	-	12.50% D	[23]
<i>Holothuria scabra</i> (BW)	Boiling at 80–90 °C	-	-	-	-	-	-	69.81% D	[23]
<i>Holothuria scabra</i> (BW)	Boiling at 80–90 °C and salted for 48 h	-	-	-	-	-	-	38.41% D	[23]
<i>Sticopus japonicus</i> (BW)	Atmospheric pressure boiling at 100 °C for 1 h	14.8% D	-	-	-	-	-	-	[62]
<i>Sticopus japonicus</i> (BW)	Atmospheric pressure steaming at 100 °C for 1 h	13.0% D	-	-	-	-	-	-	[62]
<i>Sticopus japonicus</i> (BW)	High-pressure steaming at 121 °C for 10 min under 0.21 MPa	11.6% D	-	-	-	-	-	-	[62]
<i>Apostichopus japonicus</i> (BW)	Vacuum cooking at 95 °C for 3 h under −0.04 MPa	9.95% I	0.59% I	1.64% I	-	-	1.5% I	-	[37]
<i>Apostichopus japonicus</i> (BW)	Vacuum cooking at 95 °C for 3 h under −0.04 MPa then soaking at 4 °C water for 12 h	1.33% I	0.04% D	0.28% D	-	-	0.33% I	-	[37]

HPP = high-pressure processing, I = increased and D = decreased than when found in control without any treatments. BW = body wall; IO = internal organ; GAE = gallic acid equivalents; Carb. = carbohydrates; Polysac. = polysaccharides.

3.2. Salting

The aim of salting is to preserve the sea cucumber before processing and to remove extra water from the body wall through osmotic dehydration [12,23]. Through osmotic dehydration, water is removed from the lower-concentration region of a cell to the high-concentration region through a semipermeable membrane [63]. Osmotic dehydration is required to retain the colour, aroma, and nutritional components of sea cucumbers [64]. Salt preservation effectively reduces microbial activity as bacteria, fungi, and other pathogenic organisms cannot grow in saline water due to the nature of hypertonic saline [12]. Salting is performed through dry salting followed by wet salting [12]. Coarse salt is used for preserving sea cucumbers because of its slow penetration, while fine salt may damage the skin [12,16]. In particular, 0.5 kg of coarse salt in one litre of water is recommended for wet salting to obtain a good-quality product. For a better appearance of dried sea cucumber, a ratio of the salt and sea cucumber of 1:3 has been recommended. Moreover, it is also reported to provide the body wall of the sea cucumber with hardness and elasticity against breakage during packaging [9,12,16].

3.3. Vacuum Cooking

Vacuum cooking is used to cook raw materials; however, this is carried out under a controlled temperature and time and in heat-sensitive vacuum-sealed bags [65]. This method is used to extend the shelf life of the product, increase the taste, and retain the nutritional value of meat [66].

In this method, the body wall of a sea cucumber is boiled for 15 min and then exposed to vacuum cooking through the modified heat-stable vacuum machine. This machine is involved in a steam-jacket kettle and pressure cooker vessel along with an inner plate. The boiled body wall is spread on the pressure cooker vessel. The steam-jacket kettle is set at 95 °C and the pressure cooker is set at −0.04 MPa for 3 h [37]. It is reported that the amount of protein, lipid, carbohydrate, and polysaccharide content was increased by 9.95, 0.59, 1.64, and 1.5%, respectively, compared to fresh sea cucumbers [37].

3.4. High-Pressure Steam

The technique of high-pressure steam is associated with the processing of sea cucumbers at a controlled temperature and pressure [25]. High-pressure steam is developed to inactivate the enzymatic activities, increase productivity, and retain nutritional properties and bioactive compounds [24]. Chen et al. [53] applied high-pressure steam of 0.15 MPa at 121 °C for 15 min as a pre-treatment for sea cucumber body wall processing to determine the texture profile such as hardness and chewiness (Table 3) and chemical composition, including collagen fibre. They reported a long, clear, and tight interlaced arrangement of collagen fibres using the Van Gieson staining method. Further, Gu et al. [62] reported that an 11.6% protein loss was reduced in the body wall when a sea cucumber was processed under 0.21 MPa pressure at 121 °C for 10 min than for a frozen sea cucumber. However, from both studies, it was reported that the high-pressure steam could cause the degradation of collagen fibre [53] and the hydrolysis of amino acids such as phenylalanine, leucine, asparagine, and tyrosine [62]. These effects could be due to the high pressure, duration, or high temperature. Therefore, this method can be recommended as a pre-treatment for sea cucumbers to be a suitable optimization for retaining valuable chemical compounds.

3.5. High-Pressure Processing (HPP)

High-pressure processing (HPP) is a non-thermal technology that has been used in different industries as a cold sterilization to inactivate microorganisms [7,67,68]. The covalent bonds among the substances are not affected by this pressure, and due to this, phytonutrients and sensory structures are not disrupted compared to the other methods [68]. Moreover, non-covalent bonds such as hydrogen, ionic, or hydrophobic bonds can be damaged and cause enzyme inactivation, protein denaturation, and gel property changes upon HPP [69,70]. The shelf life of asparagus is extended by the high hydrostatic pressure

at 600 MPa for 8 min using HPP [68]. In addition, HPP at 400 MPa and 600 MPa reduced the total mesophilic bacteria and enhanced the ascorbic acid and flavonoid contents, along with increasing antioxidant activity compared to other thermal treatments [71]. This is because HPP ruptures the cell membrane of the samples, and due to this, the solvent can easily penetrate the samples, improving the extraction [72].

Therefore, HPP has been used to isolate valuable chemical compounds from various species [53,71] including sea cucumbers [61,73,74]. For instance, Hossain et al. [73] reported that HPP pre-treatment at 600 MPa for 10 min has increased 32.59% of the total phenolic and 20% of the total flavonoid content of the viscera of sea cucumbers (*Cucumaria frondosa*). Further, they also reported that the total phenolic and flavonoid contents were increased by 29.21% and 59.71%, respectively, at 600 MPa for 10 min over the treatment at 200 and 400 MPa for 5 min using HPP in the body wall of *Cucumaria frondosa* (Table 4) [74]. Coroneo et al. [75] reported that this method is crucial for destroying unfavourable microorganisms and inactivating the enzymes through an alteration of macromolecules, intracellular proteins, hydrophobic bonds, and electrostatic interactions for the preservation of *Paracentrotus lividus*. Moreover, Lee et al. [76] stated that the moisture content and surface area of Asian hard clams were decreased by 0.11 and 0.9% at 500 MPa for 3 min, respectively, over the fresh ones and those marinating with soy sauce. In addition, the Greenshell™ mussel (*Perna canaliculus*) colour was darker with HPP at 500 MPa for 3 min than the colour with the control and heat treatment [77], and Gram-positive bacteria increased from 56 to 84% at 500 MPa along with the fungi that were inactivated through pressure ranging from 300 to 600 MPa using HPP in the shellfish [78]. Therefore, it can be suggested that a pressure of 100 to 600 MPa for 3 to 10 min can be used as an optimized treatment for HPP (Figure 2).

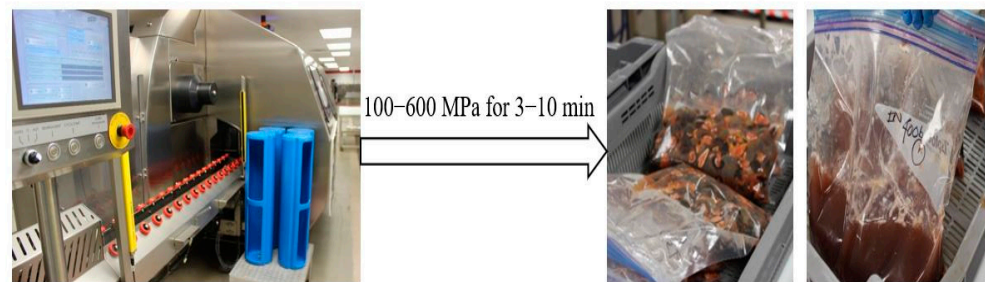


Figure 2. Processing of sea cucumbers using HPP pre-treatment.

4. Effect of Drying on the Nutritional, Biochemical, and Physiochemical Properties of Sea Cucumbers

Drying is used to reduce the moisture from sea cucumbers in order to increase shelf life and transport them from one place to another [29]. Most North American sea cucumbers are exported to Asian countries and drying plays a vital role in terms of easy transportation with a longer storage capacity [2]. The most common drying methods are sun (traditional), freeze, vacuum, cabinet, hot air, hot pump, far-infrared radiation, and microwave drying [27,48,79–81]. Some combined drying methods are also used for drying sea cucumbers, namely microwave vacuum drying [82], vacuum freeze drying [83], dielectric drying [48], a combination of electrohydrodynamic and vacuum freeze drying [84], and hybrid heat pump vacuum drying [81]. Furthermore, electricity-based drying methods, including electrohydrodynamic and high-pulsed electric fields, have been operated to increase the drying effectiveness and retain the physiochemical properties of sea cucumber [83,85]. These methods are low-temperature and high-efficiency drying methods and are utilized for shortening the processing time, protecting nutritive and bioactive properties, and improving the quality of products [24,37]. All these methods are based on removing the moisture through evaporation to prolong the shelf life of sea cucumbers during storage, packaging, and marketing [86].

4.1. Sun Drying

Traditionally, sun drying is widely used to dry sea cucumbers to control microorganisms and remove water from the product [87]. This is because microorganisms, such as bacteria, yeast, and moulds, can easily grow in an environment where water, food, and nutrients are available [86]. Sun drying is easy, cost-effective, and does not need trained labour. It can be used for a big bulk sample using a big open space under the direct sun where the local farmers do not have access to modern drying methods such as freeze drying, microwave drying, and hot air drying, which are also costly [37]. It takes temperatures around 18 °C–25 °C for 72–96 h to dry the sea cucumber product, which is sometimes challenging due to the uncontrolled natural source of drying that can fluctuate with weather and climate change [37]. Even when sea cucumbers are kept for drying under the sun, other environmental factors, such as rain, humidity, and wind, might attract pest invasions such as insects, pests, rats, dogs, birds, and many more [29]. One of the challenging characteristics of sea cucumbers during processing is their heat sensitivity and due to this uncontrolled sunlight, the quality of the product can be considerably damaged [12].

4.2. Hot Air Drying

Hot air drying is the most effective drying method to absorb water from food using the continuous flow of hot air. This process is homogenous, contamination-free, and takes less time than sun drying [37]. Even industries use this method due to the low maintenance cost and simple operational techniques [1]. Studies were conducted in hot air dryers to determine the variation of chemical composition among different drying methods such as freeze and microwave drying, where hot air was supplied at the rate of 1.5 m/s and maintained a relative humidity of 20% at 60 °C to obtain a moisture content of 6 to 7% [3,44]. Li et al. [37] stated that hot air drying at 60 °C for 48 hr was the superior processing method to obtain the nutritional and functional properties such as the total saponin, crude polysaccharide, and crude lipid percentage of sea cucumbers compared to sun drying, vacuum freeze drying, and double-distilled water cooking. Nursid et al. [30] reported that the percent of protein content increased by 16.4% via hot air drying over the fresh sea cucumber. Öztürk and Gündüz [3] reported that the percent of ash content increased by 8 and 2% in the hot air-drying method over the freeze-drying and microwave-drying methods, respectively. Moreover, the lipid percentage increased by 2% in hot air drying over freeze drying [1].

However, hot air flow dries out the surface of sea cucumber quickly; therefore, the outer layer becomes harder than the inner layer, and the moisture from the inner layer is removed slowly. As a result, it causes product shrinkage and structure deterioration as well as hampering storage ability and damaging heat-sensitive nutritional components [27].

Therefore, based on the above findings, it can be concluded that a range of hot air flow of 40–60 °C for 48–72 h could be used to optimize this method to obtain good-quality products from sea cucumbers (Figure 3).



Figure 3. Processing sea cucumbers using a hot air dryer.

4.3. Vacuum Drying

Vacuum drying is used to gently remove water or solvents from products without hampering the original product's properties using reduced pressure and low temperature [29].

At low temperatures, the solvents/ moisture transforms from liquid to vapour while products are dried through low pressure. After vacuum drying, the rehydration ratio of the products is improved with its water-holding capacity as well as porosity. The principle of vacuum drying is providing heat through conduction or microwaves, causing the removal of vapour through a vacuum system [29,51]. This method has not been reported in sea cucumbers; however, it could be a potential method to optimize sea cucumber drying to retain the product's physical and chemical properties due to the use of a low temperature and reduced pressure.

4.4. Microwave Vacuum Drying

The microwave vacuum drying method is a combined approach of a microwave and a vacuum dryer. The principle of microwave vacuum drying is to fasten the rehydration rate using the permeable microstructure. In this method, 200 W or 250 W of microwave power is applied to remove the water from the internal surface to the external surface of the body wall of sea cucumbers [82]. A microwave vacuum dryer is used to evaluate the physiochemical properties of sea cucumbers such as the rehydration ratio, water-holding capacity, and textural profile as well as nutritional composition including amino acid, hydroxyproline, and saponin content. However, high microwave power has been reported to damage the structure of collagen and accelerate amino acid degradation but did not show any significant variation in saponin content [82]. This could be due to the effect of the high temperatures (200 W to 250 W $\cong$ 100 to 150 °C) used in microwaves that might degrade the collagen [88].

4.5. Cabinet Drying

Cabinet drying is more flexible than sun drying because it protects the product from the weather, seasons, and animal attacks [89]. It is used for reducing the moisture content from the products in a controlled environment for secured storage [89]. In this method, a shallow tray is placed in the cabinet dryer, and a 1–3-inch product is placed on the tray. A fan is set up over the product to increase the airflow speed in order to accelerate the drying rate [89]. For optimum drying, hot air flow is produced from the cabinet area, and this heat transfer is controlled using a regulator [89]. Electricity or burning fuels are required to generate heat in the cabinet dryer. The evaporation rate of the moisture content is increased in the cabinet dryer via the hot air movement [89]. The drying rate is controlled by the higher temperature, air movement, and lower humidity because the higher temperature decreases the risk of microorganism attacks [89]. The dried products obtained from cabinet dryers are more effective against oxidation and pollution; however, the quality of this product can be impacted by the high temperature and hot air flow. The brownish-coloured products obtained through this method may be considered good-quality products in terms of product uniqueness and characterization [29]. Therefore, these methods can be recommended as a drying method in the sea cucumber industry to reduce moisture with appropriate optimization for retaining good-quality products.

4.6. Freeze Drying

Freeze drying is a modern drying processing method in the food industry and is often known as lyophilization. Lyophilization is utilized not only for preserving food particles but also for maintaining the original colour [48,90]. Generally, drying starts with frozen products that are maintained below low temperatures and give a crystalline form, depending on the type of product. In freeze drying, solid particles are transformed into vapour particles through sublimation, and then the water and the suspension medium become crystallized under low temperatures [91]. During sublimation, the pressure of the surrounding vapour is lower than the ice vapour [29]. The energy is provided in the form of heat, which is lower than the product's low temperature. After that, the product's surrounding pressure is increased to form a crystallized structure [29].

Freeze drying is a more beneficial and effective preservative method than the other drying methods because it maintains the yield and retains the morphological, biochemical,

and immunological characteristics, as well as reduces microbial activity and weight, and provides longer shelf life, along with the recovery ability of volatile substances [48,79]. However, the maintenance cost, energy consumption rate, drying time (i.e., 18 h), and operation cost are higher in freeze drying than in other drying methods, but it is free from any cell rupture or deformation. Even heat-sensitive molecules become stable in this method, and the quality of the dried products looks similar to fresh products since they maintain their actual colour [48,79]. For example, freeze-dried sea cucumber viscera contained 6.15% less moisture when compared to hot air drying [1], and protein content (6.58%) was also higher in freeze-dried viscera (Table 5) [3]. Moreover, the saponin and polysaccharide content increased by 0.07 and 6.25%, respectively, in the body wall of sea cucumbers using freeze drying after infrared radiation (Table 4) [60]. Based on the above literature, freeze drying with a temperature range of -40 to -80 °C for 48–72 h could be used for better appearance, texture, colour, and odour, with reduced fungal infection, in sea cucumbers (Figure 4).

Table 5. Effect of different drying methods on the proximate compositions of sea cucumbers.

Species	Drying Methods	Moisture (%)	Ash (%)	Protein (%)	Lipid (%)	References
<i>Holothuria tubulosa</i> (BW)	HAD	6.86	38.16	56.12	1.36	[3]
	FD	6.00	30.39	62.70	1.93	
	MD	6.04	32.78	59.79	1.65	
<i>Cucumaria frondosa</i> Viscera	HAD	7.84	12.49	45.79	25.69	[1]
	FD	1.79	12.53	46.96	23.19	
<i>Apostichopus japonicus selenka</i> (BW)	HAD	5.15	32.99	51	5.2	[37]
	SD	5.3	37.18	46.50	5.10	
	VFD	3.99	31.89	48	5.22	
<i>Holothuria atra</i> (BW)	SD	7.5	8.8	78.6	2.7	[30]
	Oven-Dried at 40 °C	7.2	8.8	78.8	2.6	
	Oven-Dried at 40 °C	8.4	8.5	80.6	2.4	
	Oven-Dried at 40 °C	4.5	7.3	82.9	2.4	

HAD = Hot Air Dryer; FD = Freeze Dryer; MD = Microwave Dryer; VFD = Vacuum Freeze Dryer; SD = Sun Drying; BW = Body Wall.

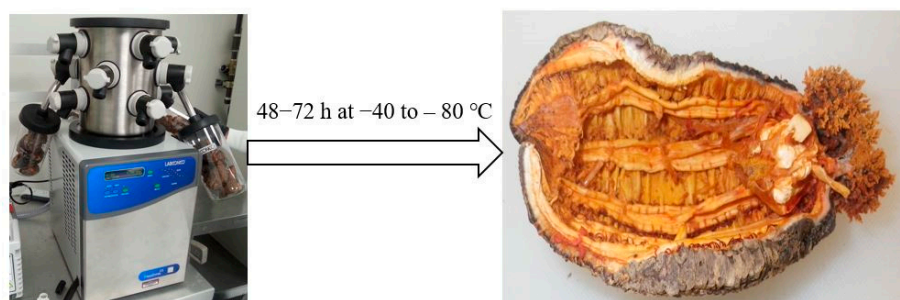


Figure 4. Processing of sea cucumbers using a freeze dryer.

Therefore, processing strategies for sea cucumbers, including pre-treatments and drying methods, are crucial parts of obtaining quality products. Different pre-treatments combined with different processing techniques and drying methods can greatly affect the proximate composition as well as the content of bioactive compounds such as phenolics, saponin, polysaccharides, and collagen (Tables 4 and 5). These compounds possess a significant potential to be a candidate in the food, pharmaceutical, and nutraceutical industries due to their wide range of bioactivities [92].

5. Challenges and Future Perspectives of Sea Cucumber Processing

After harvesting, autolysis starts in sea cucumbers because of endogenous enzymes, microbial attacks, and other environmental factors that can degrade the sea cucumber body composition. Due to this, conventional boiling pre-treatment is required to inactivate the endogenous proteinases to stop the autolysis [93]. However, appropriate temperature and time are crucial for boiling to obtain a good-quality sea cucumber. These two factors can be optimized in terms of the thickness and texture of various species of sea cucumbers. High temperatures can significantly impact the nutritional quality of sea cucumber as boiling above 100 °C drastically reduces the amino acid content [26]. Moreover, the collagen fibre of sea cucumber could be broken and denatured in the range of the temperature from 60 to 100 °C [26,55]. Further, boiling was reported to cause the loss of minerals, proteins, carbohydrates, saponins, and spermidine in sea cucumbers by 25%, 11%, 33%, 41%, and 100% (*w/w*), respectively [47].

However, modern processing techniques such as high-pressure steam and steaming cause 3.2% and 1.4% less protein losses, respectively, in the body wall of sea cucumber compared to traditional boiling. Though a high temperature during processing resulted in the hydrolysis of some proteins and amino acids, most of the amino acids, such as phenylalanine, leucine, asparagine, and tyrosine, remained stable [62]. HPP can deactivate the autolytic enzyme, but enzymes cannot be fully denatured using this method due to the product quality potentially deteriorating during storage [53,58]. Further, sea cucumber texture quality, cooking yield, and water-holding capacity are affected by enzyme activity and protein denaturation, which are related to the various heating treatments [58].

Therefore, boiling pre-treatment with a higher temperature may reduce the content of protein, total sugar, saponin, and inorganic compounds, subsequently causing metabolite changes in sea cucumbers. However, proteins, lipids, and other components may be degraded/unaffected after boiling, but the release of amino acids and fatty acids is usually improved. Boiling is useful for the sea cucumber processing industries to prevent autolysis as well as maintain the overall chemical compositions [15,47,94–96]. Zhang et al. [58] reported that steaming at 100 °C for 30 min is good for the long-term preservation of sea cucumbers and boiling at 100 °C for 45 min is applicable for obtaining a high cooking yield and protein content. Hence, the integration of modern techniques along with traditional boiling at a proper temperature and time would provide a rationale to overcome the challenges of conventional boiling to obtain a good-quality product.

Traditionally, salting is significantly more valuable for preserving the sea cucumber. However, local harvesters use fine salt, which damages the skin quality because of its high penetration [12]. Therefore, using coarse salt for salting pre-treatment is recommended to protect the sea cucumber body wall composition [9].

After pre-treatment, drying is required for further processing/preservation, such as grinding to extract nutrients and bioactive compounds, storage as edible products, and packaging as well as transportation. Sun drying is the most popular method for drying sea cucumbers conventionally. However, product quality can be drastically hampered by sun drying due to uncontrolled sunlight and other environmental contaminants, and products might be affected by insects, pests, rats, dogs, and many more [12,29]. Local people use sun drying only for the body wall of sea cucumbers. However, sun drying is not useful for the drying of other internal organs, such as the viscera and aquapharyngeal bulbs of sea cucumbers. In this context, today, there are many modern drying methods used not only by industries but also by local farmers, such as freeze drying, hot air drying, and microwave drying [1,3,29,82]. Among them, freeze drying has been reported as one of the best methods of drying sea cucumber to retain the chemical composition as well as product taste, quality, colour, and texture with a high market value [1,3].

This review emphasizes the impact of different pre-treatments and drying methods on the nutritional compositions of sea cucumbers, based on which a rational processing method can be developed considering all the value aspects of sea cucumbers. Boiling as a pre-treatment has been recognized to inactivate endogenous enzymes with many

challenges reported here with the probable integration of modern methods to overcome the risk of quality loss. To prolong the shelf life and obtain the chemical composition, various types of drying methods are used after pre-treatment. Based on the above information, future work will focus on different pre-treatments and drying methods of sea cucumbers, but more emphasis will be placed on optimization techniques and retaining the nutritional compositions. This review on sea cucumbers can further differentiate the better processing methods, the sustainability of the advanced technology, and focus on obtaining nutritional quality and feasibility for the industry, which could be the best opportunity for the fishery.

6. Conclusions

Sea cucumbers are a promising sector around the world due to their nutraceutical and pharmaceutical properties. However, their chemical composition degrades after harvesting, depending on the processing conditions. Different pre-treatments and drying methods are used to extend their shelf life and storage capacity and extract their chemical components. Advanced technology has played a vital role in extracting their chemical composition without the rupture of the chemical structure in contrast to traditional methods. Various pre-treatments and drying methods are helpful for preserving not only nutritional compositions but also bioactive compounds. Therefore, ideal pre-treatments and drying methods may help scientists and the industry's community to find out the valuable components from sea cucumbers that improve their potential to be used in the cosmetic, pharmaceutical, and nutraceutical industries. Finally, HPP pretreatment and freeze drying could be used as a suitable method for obtaining better-quality products.

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