Food Bioscience 44 (2021) 101397

Contents lists available at ScienceDirect

Food Bioscience

journal homepage: www.elsevier.com/locate/fbio

Exploring the feasibility of developing novel gelatin powders from salted, dried cannonball jellyfish (*Stomolophus meleagris*)

Peter G. Chiarelli [a], Ronald B. Pegg [b], Govindaraj Dev Kumar [c], Kevin Mis Solval [a,*]

[a] Department of Food Science and Technology, University of Georgia, Griffin, GA, 30223, USA
[b] Department of Food Science and Technology, University of Georgia, Athens, GA, 30602, USA
[c] Center for Food Safety, University of Georgia, Griffin, GA, 30223, USA

ARTICLE INFO

Keywords:
Cannonball jellyfish
Jellyfish gelatin
Marine collagen
Bloom strength
Acid hydrolysis
Rheology

ABSTRACT

Cannonball jellyfish, often commercialized as salted, dried jellyfish (SDJ), is an emerging fishery in the USA and a great source of collagen, which can be utilized for developing novel marine gelatin powders. The aim of this study was to determine the feasibility of producing gelatin powders with gelling properties from SDJ using a mild acid hydrolysis and freeze-drying procedure as well as to evaluate their physico-chemical properties. The findings revealed that the resultant gelatin powders had a moisture (g/100 g, dry basis, d.b.), crude protein (g/100 g, d.b.), ash content (g/100 g, d.b.) and water activity values of 4.82, 29.54, 56.61, and 0.09, respectively. Sodium, Al, and S were the main minerals detected in the jellyfish gelatin powders, which were agglomerated and had irregular morphologies with a mean particle size of 12.8 μm. Gels prepared with 5, 6.67, and 10% (w/v) jellyfish gelatin powder had Bloom values lower than 4.2 g; melting temperatures between 15.09 and 16.12 °C and their rheological behavior was effectively characterized by the Herschel-Bulkley flow model, which revealed non-Newtonian behavior and shear thinning phenomena. Higher apparent viscosities, yield stress, and consistency index values were observed in the gels prepared at higher concentrations of jellyfish gelatin powders and at lower evaluated temperatures. This study illustrates (for the first time) the feasibility of producing novel marine gelatin powders from SDJ, which have the potential to be used as gelling, thickening and/or binding agents in several food applications.

1. Introduction

Since the 1950s, global jellyfish populations have been increasing and jellyfish "blooms" (i.e., outbreaks of jellyfish) are being reported at higher frequencies worldwide (Brotz et al., 2012). This affects local economies by interfering with tourist activities, coastal mariculture operations, decreasing fishing efficiencies as well as leading to ecologically imbalances (Patwa et al., 2015). Increasing jellyfish populations have been linked to global changes, including but not limited to eutrophication and global warming, driven by an increased number of human activities (Duarte et al., 2013). Jellyfish have been consumed in several Asian countries for over a thousand years in a salted, dry form, where it is considered a gourmet delicacy. According to Leone et al. (2015), jellyfish are appreciated not only for their texture and taste, but also for their low levels of fat and cholesterol and high contents of vitamins and minerals. Not surprisingly, jellyfish are not a common food in the diet of Western consumers. However, the ongoing search for foods obtained from sustainable sources and the increases of edible jellyfish species will likely lead to their consumption in Western societies in various forms. Nevertheless, introducing jellyfish-based products into Western markets calls for food innovation. A "Future of Food Report" (2019) published by the UK-based supermarket chain Sainsbury's stated that jellyfish might be a food of the future due to their "explosive growth" and nutritional content. As a rich-source of collagen, edible jellyfish can be used as a raw material for novel food ingredients like gelatin.

Gelatin is a water-soluble protein hydrolysate obtained from the partial hydrolysis of collagen. It is widely utilized by the food, cosmetic, and pharmaceutical industries because of its great functionalities afforded by its surface-active properties (Chandra & Shamasundar, 2015). Food-grade gelatins are used in confections, low-fat spreads, dairy products, baked goods, meat products, and for lowering caloric density (Karim & Bhat, 2009).

According to Huang et al. (2019), commercial gelatins are mostly obtained from pork and bovine by-products. Gelatins from mammalian sources are, however, under constraints and skepticism because of

* Corresponding author. 184 Melton Building, 1109 Experiment Street, Griffin, GA 30223, USA.
E-mail address: kmissolval@uga.edu (K. Mis Solval).

https://doi.org/10.1016/j.fbio.2021.101397
Received 7 July 2021; Received in revised form 28 September 2021; Accepted 29 September 2021
Available online 1 October 2021

Abbreviations

ANOVA	Analysis of variance
a_w	Water activity
CBJ	Cannonball jellyfish
d.b.	Dry basis
DH	Degree of protein hydrolysis
DIW	Deionized water
DVB	Dynamic viscoelastic behavior
GMIA	Gelatin Manufacturers Institute of America, Inc.
H-SDJ	Hydrolyzed salted, dried cannonball jellyfish
LVR	Linear viscoelastic region
MCR	Modular compact rheometer
OPA	*o*-phthalaldehyde
SDJ	Salted, dried cannonball jellyfish
SEM	Scanning electron microscopy
T_m	Melting temperature
USDA	United States Department of Agriculture
U-SDJ	Unhydrolyzed salted, dried cannonball jellyfish
w.b.	Wet basis

social, cultural, and health-related concerns (Karim & Bhat, 2009). This is pressuring the food industry to develop gelatins from alternative sources (i.e., fish by-products and even jellyfish) (Huang et al., 2019; Rodsuwan et al., 2016). Karim and Bhat (2009) mention several challenges associated with the production of marine gelatins including poor rheological properties, variable quality, off-flavors, and low yields. Due to these challenges, continued research on marine gelatins is needed to improve the quality of these products.

Marine gelatins have unique functional properties like lower gelling and melting temperatures compared to mammalian gelatins, which can allow for a quick release of encapsulated aromas and flavors (Borza et al., 2010; Karim & Bhat, 2009; Li et al., 2009). The quality of gelatins is often determined by their viscoelastic properties, Bloom strength, and melting temperature, which are affected by the physicochemical properties of the raw materials and the processing methods employed (Huang et al., 2019; Niu et al., 2013). The desired Bloom strengths and viscoelastic properties of gelatins are ultimately pre-determined by the intended food application. Additionally, temperature and solid concentration can affect the properties of thermo-reversible gelatin gels (Sarbon et al., 2015).

Studies have described the production of marine gelatins from fish and fish by-products, but only a handful have reported the production of gelatins from edible jellyfish species: *Lobonema smithii* (Chancharern et al., 2016; Rodsuwan et al., 2016), *Acromitus hardenbergi* (Khong et al., 2016), *Rhopilema hispidum* (Cho et al., 2014), and *Rhopilema esculentum* (Zhuang et al., 2010); noteworthy is that each study uses harsh chemicals such as HCl, KOH, NaOH, and H_2SO_4 to hydrolyze the jellyfish collagen. Additionally, mild acid hydrolysis using citric acid has only been employed to hydrolyze fish skin collagens (Niu et al., 2013; Nurilmala et al., 2020). Importantly, the feasibility of using mild acid hydrolysis to hydrolyze the salted, dried jellyfish (SDJ) to produce jellyfish gelatins has not been reported in the scientific literature.

Cannonball jellyfish (CBJ) is an emerging commercial fishery in the state of Georgia, USA. (Fluech, 2018). CBJ is also an emerging fishery in other parts of North America, including the Gulf of California, wherein 2018 approximately 670,000 metric tons of total landings of CBJ were estimated (María Esther et al., 2021). Unfortunately, limited information regarding the available biomass of CBJ in the Atlantic coast of the USA is currently available. Notably, researchers have suggested that climate change and global warming will increase the long-term biomass and catch potential of CBJ (up to 10%) in the coming decades (Cisneros-Mata et al., 2019). Once caught, fresh CBJ is immediately processed in coastal Georgia and commercialized as SDJ, which is mainly exported to Asian markets. Currently, SDJ is still the only commercial product of the US jellyfish industry despite the tremendous potential to develop alternative novel products. Unfortunately, tariffs on China, a major importer of American SDJ, and a low domestic demand for this product have caused uncertainty for the US jellyfish industry. Therefore, finding alternative uses for this abundant CBJ is important to ensure the long-term viability of this emerging industry. Additionally, based on the opportunities presented in the Western markets regarding the trends for novel marine collagens, our team believes that there is a great potential to capitalize on the opportunity to build a jellyfish-based products industry in the USA.

To our knowledge, no studies have reported on the feasibility of producing gelatin powders from SDJ. We hypothesize that the collagen present in the SDJ can be successfully hydrolyzed to give novel gelatin powders with gelling properties. Hence, the main objective of this study was to determine the feasibility of producing jellyfish gelatin powders with gelling properties from SDJ using mild acid hydrolysis and a freeze-drying procedure, and then to characterize the physico-chemical properties of the resulting powders.

2. Materials/methods

2.1. Materials

SDJ were purchased from Golden Island International, LLC (Darien, GA, USA). Food-grade citric acid (Milliard, Lakewood, NJ, USA), disodium tetraborate decahydrate (98.5% purity, Millipore Sigma, St. Louis, MO, USA), sodium dodecyl sulfate (SDS) (99% purity, Millipore Sigma), *o*-phthalaldehyde (OPA) (98% purity, Millipore Sigma), dithiothreitol (DTT) (98% purity, Millipore Sigma), and L-serine (98.5% purity, Millipore Sigma) were used in this study.

2.2. Preliminary characterization of SDJ

SDJ were puréed in a blender (Model BL610, NINJA, SharkNinja Operating, LLC, Needham, MA, USA) and then analyzed for moisture and ash contents by AOAC Official Methods 934.01 (oven drying) and 938.08 (furnace combustion), respectively (AOAC, 2019). Crude protein was determined by following the Dumas method using an automated nitrogen analyzer (Rapid N Exceed, Elementar, Langenselbold, Germany) described by Jung et al. (2003). In short, approximately 250 mg of dry sample and aspartic acid (nitrogen calibration standard) (Part Number E6010, Elemental Microanalysis Ltd., Okehampton, UK) were individually weighed on tin foil then tightly wrapped and placed onto the Rapid N Exceed. The combustion tube temperature was set to 960 °C, dosing for blanks was set to 50 mL of O_2/min while dosing for the samples was set to 150 mL of O_2/min. Khong et al. (2016) reported a conversion factor of 5.8 to determine the % crude protein content for jellyfish. Water activity (a_w) was obtained with a water activity meter (AquaLab Series 3 TE, Decagon Devices, Inc., Pullman, WA, USA). Color values (L*, a*, b*, chroma, and hue angle) were determined using a Lab Scan XE Colorimeter (Hunter Associates Lab., Inc., Reston, VA, USA).

2.3. Production of gelatin powders from SDJ

The process diagram for producing gelatin powders from SDJ is shown in Fig. 1. One kg of SDJ (~16–20 jellyfish) was rinsed and soaked in tap water overnight for rehydration. Rehydrated SDJ were chopped, soaked in a citric acid solution (1.5%, w/v) for 10 min, drained, blended for 12 min, and homogenized with an ultra-shearing homogenizer (Homogenizer 850, Fisher Scientific UK, Ltd., Loughborough, UK) at 8000 rpm for 6 min and then 10000 rpm for 8 min. Liquid SDJ was incubated at 60 °C for 4.5 h in a water bath (Model 2872, Precision, Thermo Electron Corp., Waltham, MA, USA) to allow for the hydrolysis of the collagen. The hydrolyzed SDJ were frozen at −4 °C for 12 h then

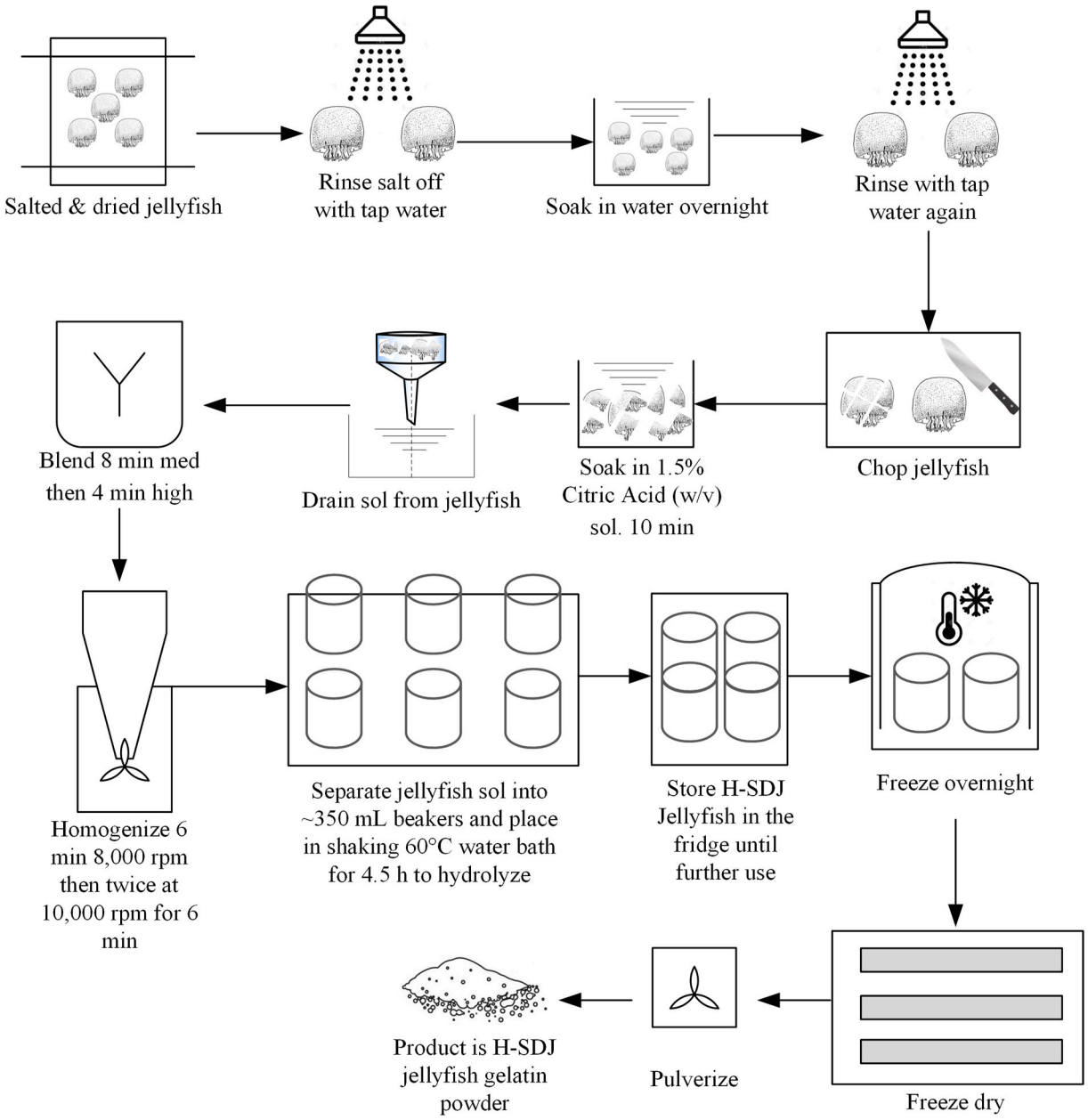

Fig. 1. Process diagram to turn salted, dried jellyfish (SDJ) into hydrolyzed (H-SDJ) gelatin powder.

freeze-dried in a lyophilizer (Virtis, The Virtis Co., Gardiner, NY, USA). The freeze-dried sample was then pulverized using an electric grinder (Model SUS304, Slsy & Mooncool, Shanghai, China) to obtain hydrolyzed SDJ (H-SDJ) powders. Concurrently, unhydrolyzed SDJ (U-SDJ) powders were prepared according to the aforementioned method (except the washing and hydrolysis steps) and used as the control. Both, H-SDJ and U-SDJ powders were stored in desiccators for a maximum of 6 months at room temperature (~20 °C) until ready for analysis.

2.4. Degree of protein hydrolysis (DH)

The DH, or percentage of cleaved peptide bonds, was measured according to the OPA method described by Nielsen et al. (2001). Briefly, sample aliquots (9 mL) of liquefied SDJ were taken during the hydrolysis procedure at different times intervals over 24 h. Samples were immediately placed into an ice-water bath to stop hydrolysis and then were stored for a maximum of 24 h at 4 °C until further analysis. The OPA reagent, serine, and sample solutions were prepared according to Nielsen et al. (2001). A Genesys 30™ spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA) and polystyrene spectrophotometry cuvettes (Cat No. 759070D, BrandTech Scientific, Inc., Essex, CT, USA) were used. Each sample was run in triplicate, and the DH was calculated according to Eqs. (1) and (2).

$$Serine - NH_2 = \frac{OD_{sample} - OD_{blank}}{OD_{standard} - OD_{blank}} * 0.9516 \frac{meqv}{L} * 0.1 * \frac{100}{X * P} \quad (1)$$

$$DH = \frac{h}{h_{tot}} * 100\% \quad (2)$$

where, serine–NH_2 = meqv serine NH_2/g protein; X = g sample (in this study, 1.0 g); P = protein % in sample; 0.1 is the sample volume in liters (L). h = (Serine–NH_2 – β)/α meqv/g protein, where α, β, and h_{tot} are 0.796, 0.457, and 11.1, respectively (Nielsen et al., 2001).

2.5. Physicochemical properties of H-SDJ powders

2.5.1. Moisture content and a_w

The moisture content of the prepared powders was determined by AOAC Official Method 934.01 (AOAC, 2019) using an Isotemp® vacuum oven (Model 281 A, Thermo Fisher Scientific, Waltham, MA, USA). Water activity was measured using an Aqualab water activity meter (Decagon Devices, Inc.).

2.5.2. Ash content

The ash content of the powders was determined by following AOAC Official Method 923.03 for ash analysis. Briefly, powder samples were weighed into preconditioned porcelain crucibles, which were then placed into a muffle furnace (Model F-A170, Thermolyne, Dubuque, IA, USA) programed at 550 °C for ~18 h. The samples were then taken out, cooled, weighed, and the ash content calculated using Eq. (3).

$$Percent\ ash = \frac{Sample\ mass\ after\ ashing\ (g)}{Original\ sample\ mass\ (g)} * 100 \quad (3)$$

2.5.3. Color

Color was measured using a Lab Scan XE colorimeter (Hunter Associates Lab., Inc.) and the values were reported using the CIE L.A.B color scale (L*, a*, and b* values). Plastic Petri dishes (100 × 15 mm) were filled with powder until the bottom was covered, then the color was measured in triplicate and the values averaged. Afterwards, chroma and hue angle values were calculated according to the method reported by Solval et al. (2012).

2.5.4. Mineral analysis

The mineral analysis of H-SDJ and U-SDJ powders was carried out at the UGA Soil, Plant, and Water laboratory (Athens, GA). Briefly, powdered samples were dried for ~24 h at 65 °C, ground in a Wiley mill (Model 3, Swedesboro, NJ, USA) set with a 2-mm screen then passed through a 20-mesh (841 μm) screen. The samples were then digested following EPA Method 3052 (Anonymous, 1996). The digests (solutions) were transferred quantitatively into volumetric flasks and brought to 100 mL with deionized water (DIW). Solutions were analyzed for various minerals following EPA Method 200.8 by inductively coupled plasma - optical emission spectroscopy (ICP-OES) (Spectro Arcos FHS16, Kleve, Germany) (Creed et al., 1994). All results were reported in percent or parts per million (mg kg^{-1}).

2.5.5. Particle size distribution

Powders were sieved (20-mesh size, 841 μm) before particle size determination with a particle size analyzer (Model PSA 1190, Anton Paar, Graz, Austria). Powders were individually fed into the machine where the light scatter pattern was analyzed. Each sample utilized a 10 s run time with dispersion parameters of 40% vibrator duty cycle, 40 Hz vibrator frequency, and 120 kPa of air pressure. The light scatter pattern was used to quantify the particle size distribution by the Fraunhofer reconstruction method. The data was reported as D_{10}, D_{50}, and D_{90}, which are the average volume diameters of the particles at 10, 50, and 90% cumulative volume, respectively. The span value (i.e., spread of particles) was calculated by following the method described by Mis Solval et al. (2016).

2.5.6. Scanning electron microscopy (SEM)

SEM images were collected using a scanning electron microscope (1450 EP, Carl Zeiss MicroImaging, Thornwood, NY, USA) at the UGA Georgia electron microscopy facility (Athens, GA) described by Jiang et al. (2020). Briefly, powder samples were sputtered-coated with gold and images were collected using an acceleration potential of 2 kV, as this voltage provided the best sample morphologies.

2.5.7. Determination of bloom strength

The official method of the Gelatin Manufacturers Institute of America, Inc. (GMIA) was adapted to determine the Bloom strength of the powders (GMIA, 2019, pp. 9–12). Gelatin solutions of 5, 6.67 and 10% solids (w/v) were prepared with either H-SDJ or U-SDJ and DIW using Bloom jars (59 mm height x 85 mm diameter; Brookfield Engineering, Middleboro, MA, USA). Solutions were allowed to swell for 2 h at room temperature (22–24 °C) and gelation was achieved by heating the jars at 65 °C for 15 min. The gels were held for 20 min at room temperature to cool. Jars were then placed in a cooling water bath at 10 °C for 17 ± 1 h to allow formation of the gelatin gels. Bloom strength of the gels was measured with a texture analyzer (TA.XT Plus, Stable Micro Systems Ltd, Godalming, UK) at a 4-mm penetration depth, 1 mm/s with a 12.7 mm diameter probe. The peak force (g) was reported as the Bloom strength.

2.5.8. Dynamic viscoelastic behavior (DVB)

The DVB of 5, 6.67 and 10% (w/v) gelatin solutions (prepared with H-SDJ powders) was characterized. After maturation, the gels were placed in a 4 °C refrigerator overnight. Samples were removed from refrigeration and immediately loaded onto the Peltier plate of a modular compact rheometer (MCR Model 92, Anton Paar, Graz, Austria) equipped with a temperate control device (H-PTD 200/Air/18 P, Anton Paar, Graz, Austria). The gel sample was trimmed and equilibrated at the selected temperature (−2, 4, and 10 °C) for 2 min before testing. The linear viscoelastic region (LVR) of the samples was determined before conducting the DVB measurements (data not shown). The % strain mode was selected for the LVR measurement in the range of 0.01–10. A 0.5% strain was employed for all DVB determinations, which included both temperature and frequency sweeps.

2.5.8.1. Temperature sweeps. Temperature sweeps were conducted from 0 to 20 °C at a heating rate of 1 °C/min (linear ramp). The Peltier plate of the MCR was set to a starting temperature of 0 °C, then the sample was placed between the Peltier plate and a parallel measuring plate (25 mm diameter, Anton Paar, Graz, Austria); the gap was set to 1000 μm and the frequency of oscillation was 10 Hz. Values of the storage modulus (G′), loss modulus (G″), and tan δ (G″/G′) were recorded and plotted against temperature. The melting temperature of the gelatin gels was determined as the crossover point of G′ and G″, as described by Chandra and Shamasundar (2015).

2.5.8.2. Frequency sweeps. Frequency sweeps of the gels were carried out at −2, 4, and 10 °C. The Peltier plate of the MCR was set to one of the starting temperatures and then the sample was placed between the Peltier plate and a parallel measuring plate (25 mm diameter); the gap was set to 300 μm. Frequency was in the range of 0.1–50 Hz at a strain of 0.5%. Values of the storage modulus (G′), loss modulus (G″), and tan δ (G″/G′) were recorded and plotted as a function of the angular frequency (ω) (rad/s) at a given temperature.

2.5.9. Flow properties (shear stress sweep)

Shear stress sweeps of gelatin solutions (5, 6.67, and 10% H-SDJ powders, w/v) were conducted at −2, 4, and 10 °C using the MCR. The Peltier plate temperature was set then the sample was placed between the Peltier plate and a parallel measuring plate (25 mm diameter); the gap was set to 300 μm. Shear stress was evaluated at shear rates (ramp linear) from 1 to 100 (s^{-1}). The flow curve data was used to select the best-fit rheological flow model, which was based on the coefficient of determination. The Herschel-Bulkley model (Eq. (4)) was selected to characterize the flow behavior of the gelatin gels.

$$\tau = \tau_0 + k\dot{\gamma}^n \quad (4)$$

where, τ is the shear stress (Pa), τ_0 is the yield stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), k is the consistency index (Pa s^n); and n is the flow behavior index (dimensionless).

Table 1
Characterization and physicochemical properties of whole salted, dried jellyfish (SDJ), unhydrolyzed salted and dried jellyfish (U-SDJ) powder and hydrolyzed SDJ (H-SDJ) powder[1].

Properties	SDJ	U-SDJ	H-SDJ
Moisture (g/100 g, d.b.)	70.68 ± 0.38[a]	1.08 ± 0.25[b]	4.82 ± 0.32[c]
Water activity (a_w)	0.76 ± 0.01[a]	0.09 ± 0.00[b]	0.09 ± 0.02[b]
Ash (g/100 g, d.b.)	88.51 ± 0.02[a]	88.53 ± 0.14[a]	56.61 ± 0.13[b]
Crude protein (g/100 g, d.b.)	7.04 ± 0.62[a]	6.07 ± 0.12[a]	29.54 ± 0.15[b]
Bloom (g) 5% (w/v)	<1.0	<1.0	<1.0
Bloom (g) 6.67% (w/v)	<1.0	<1.0	3.4 ± 0.3[a]
Bloom (g) 10% (w/v)	<1.0	<1.0	4.2 ± 0.3[a]
L*	28.12 ± 0.96[a]	77.44 ± 0.02[b]	73.09 ± 0.05[c]
a*	3.76 ± 0.65[a]	0.52 ± 0.04[b]	1.79 ± 0.03[c]
b*	16.80 ± 2.09[a]	4.14 ± 0.05[b]	8.02 ± 0.02[c]
Hue angle (°)	78.48 ± 1.24[a]	82.87 ± 0.54[b]	77.43 ± 0.21[a]
Chroma	17.29 ± 2.15[a]	4.18 ± 0.05[b]	8.21 ± 0.02[c]

Values with a < symbol were below the detection limit of the TA.XT texture analyzer.
[1] Values are means ± standard deviation of triplicate determinations.
[a] Means with different letters in the same row are significantly different ($p < 0.05$).
[b] Means with different letters in the same row are significantly different ($p < 0.05$).
[c] Means with different letters in the same row are significantly different ($p < 0.05$).

Furthermore, apparent viscosities of the gelatin solutions (5, 6.67, and 10% H-SDJ powders, w/v) were determined from −2 to 20 °C at a heating rate of 1 °C/min with a shear rate of 100 s^{-1}.

2.6. Statistical analysis

Experiments and analyses were conducted in triplicate. Analysis of variance (ANOVA) and post-hoc Tukey's studentized range tests ($\alpha = 0.05$) were conducted to determine the statistical significance of the observed differences among the means. For the analysis of the Herschel-Bulkley model parameters, a two-way ANOVA (temperature and solid concentration) and a post-hoc Tukey's studentized range tests ($\alpha = 0.05$) were employed to determine the statistical significance of observed differences among the means. Statistical analysis was performed using RStudio statistical software version 1.2.5033 (RStudio, Inc. Boston, MA, USA).

3. Results and discussion

3.1. Preliminary characterization of SDJ

The SDJ had a moisture content of 70.68 (g/100 g, wet basis, w.b.) (Table 1). According to Zhu et al. (2012), salt reduces moisture; whereas, alum precipitates collagen, disinfects, and hardens jellyfish tissues. Khong et al. (2016) reported similar findings for other species of edible jellyfish. The a_w values of the SDJ were 0.76, which indicates microbiological stability at room temperature. SDJ samples exhibited a dark yellowish color. The dark color of SDJ samples may be due to the presence of polyphenols entrapped in different tissues of the jellyfish (Leone et al., 2019). The ash content (g/100 g, dry basis, d.b.) of SDJ was 88.51 (Table 1). The crude protein content (g/100 g, d.b.) did not significantly differ from SDJ (7.04) to U-SDJ (6.07) but appeared to significantly ($p < 0.05$) increase in H-SDJ to 29.54. This may be due to the removal of excess minerals by washing, which concentrated the proteins within H-SDJ (Table 1). It has been reported that SDJ contains ~16–25 (g/100 g, w.b.) salt, ~5.5 (g/100 g, w.b.) crude protein, and provides 36 kcal per 100 g (Hsieh et al., 2001; USDA, 2009). Understanding the original composition of SDJ is critical for developing customized food ingredients with tailored functional properties.

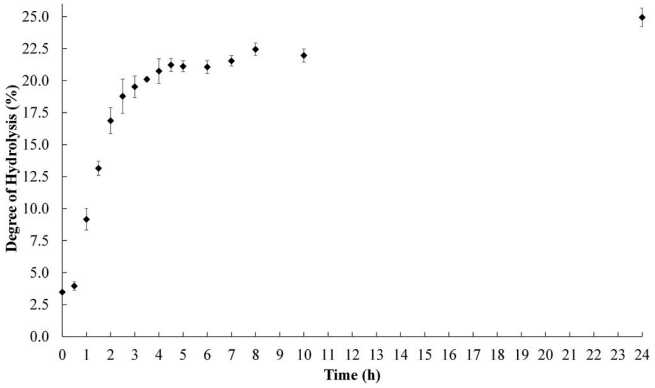

Fig. 2. Degree of hydrolysis of the salted, dried jellyfish (SDJ) over 24 h in a 60 °C waterbath using the *o*-phthaldialdehyde (OPA) method.

Table 2
Mineral profile of unhydrolyzed salted and dried jellyfish (U-SDJ) and hydrolyzed-SDJ (H-SDJ) powders[1].

Element	Units	U-SDJ	H-SDJ
Ca	(g/100 g, d.b.)	0.10 ± 0.004	0.08 ± 0.002**
K	(g/100 g, d.b.)	0.20 ± 0.02	0.13 ± 0.01**
Mg	(g/100 g, d.b.)	0.15 ± 0.01	0.11 ± 0.002***
P	(g/100 g, d.b.)	0.02 ± 0.001	0.11 ± 0.003***
S	(g/100 g, d.b.)	0.21 ± 0.01	0.31 ± 0.01***
Al	(ppm, d.b.)	970 ± 60	4300 ± 18***
B	(ppm, d.b.)	<2.0	<2.1
Cd	(ppm, d.b.)	<0.8	<0.8
Cr	(ppm, d.b.)	<1.0	15.78 ± 0.32***
Cu	(ppm, d.b.)	<1.5	16.81 ± 0.91***
Fe	(ppm, d.b.)	9.0 ± 1.9	127 ± 1.30***
Mn	(ppm, d.b.)	<2.0	<2.0
Mo	(ppm, d.b.)	<1.0	<1.0
Na	(ppm, d.b.)	370,000 ± 11,000	230,000 ± 1100***
Ni	(ppm, d.b.)	<1.0	13.68 ± 0.54***
Pb	(ppm, d.b.)	<2.0	3.53 ± 1.37
Zn	(ppm, d.b.)	3.92 ± 0.50	14.58 ± 0.31***

Values with a < symbol were below the detection limits of the inductively coupled plasma - optical emission spectroscopy (ICP-OES).
*denote a significant difference ($p < 0.05$).
1 Values are means ± standard deviation of triplicate determinations.
**($p < 0.01$).
***($p < 0.001$) between U-SDJ and H-SDJ gelatins.

3.2. Degree of protein hydrolysis (DH)

The initial DH was 3.48% (Fig. 2), which may be due to having soaked the SDJ in the citric acid solution for 10 min prior to the hydrolysis step. Chang et al. (2010) reported a decrease in the thickness of fiber diameter and perimysial (sheath of connective tissue) during the marination of collagen-containing tissues with weak organic acid solutions, including citric acid. During incubation at 60 °C, the DH rapidly increased from 3.96 to 20.11% during the span of 30 min to 3 h. Roslan et al. (2015) reported similar observations during the hydrolysis of tilapia skin at 60 °C, where the largest increase in the DH was observed at the beginning of hydrolysis. The rate of acid hydrolysis is typically high at the onset of hydrolysis due to rapid cleavage of peptide bonds then begins to level off overtime (Senphan & Benjakul, 2014; Shahidi et al., 1995). After 3 h, the DH reached steady-state conditions at ~21% for the next 10 h. Over the next 14 h, the DH increased by only 4%–24.94%, which is where the plateau affect can be observed. This may be due to a decrease or total cleavage in the number of hydrolysis sites and/or inhibition of hydrolysis due to the increased presence of products (Senphan & Benjakul, 2014; Shahidi et al., 1995). A similar DH (27.8%) was reported for the hydrolysis of the jellyfish *Rhopilema esculentum* with trypsin and properase E (Zhuang et al., 2009). No studies have reported

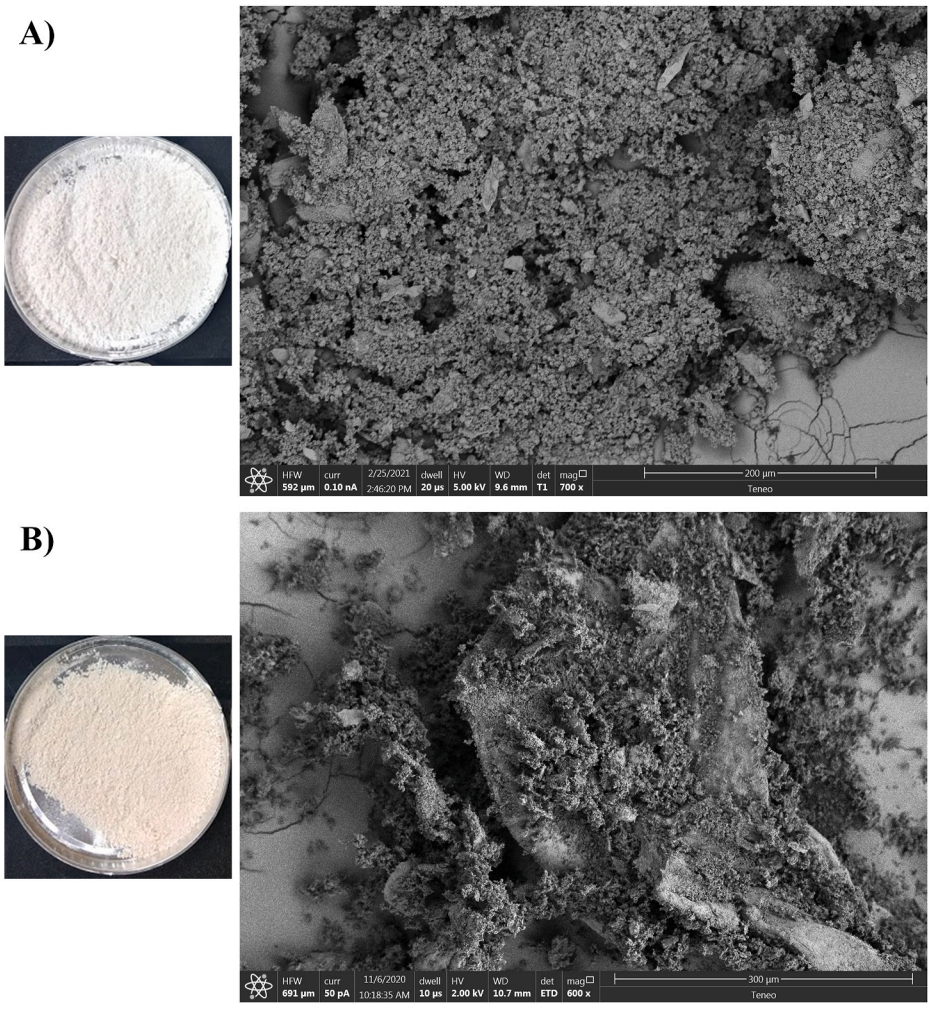

Fig. 3. A) Powder (*left*) and scanning electron microscopy (SEM) image (*right*) of unhydrolyzed salted, dried jellyfish (U-SDJ); and B) Powder (*left*) and SEM (*right*) image of hydrolyzed salted, dried jellyfish (H-SDJ).

the DH of SDJ using a citric acid solution. The DH obtained in this study of ~21% after 4.5 h is very close to an expected range of 15–20% after 5 h of hydrolysis, as reported by Roslan et al. (2015). Acid hydrolysis is considered a cost-effective method to produce protein hydrolysates for applications in the food/feed industry (Wisuthiphaet et al., 2015).

3.3. Physicochemical properties of H-SDJ powders

3.3.1. Moisture content and a_w

H-SDJ had significantly ($p < 0.05$) higher moisture contents than U-SDJ powders (Table 1). This may be due to U-SDJ possessing more minerals, especially Na (Table 2) (Boudhrioua et al., 2009). Bovine and porcine gelatin powders have a moisture content (g/100 g) in the range of 9–12 (Rahman et al., 2008). Jellyfish gelatin powders prepared from *Lobonema smithii* and *Rhopilema hispidum* via oven drying had moisture contents (g/100 g) of 6.8 and 12.2, respectively (Cho et al., 2014; Lueyot et al., 2020). The lower moisture of H-SDJ and U-SDJ powders compared to the other jellyfish gelatins may be due to an extensive freeze-drying process and/or to the excessive salt found in these samples. Additionally, a variety of factors may influence moisture and the a_w of dried powders including drying and storage conditions, number of solutes, and chemical composition of the product. Both, H-SDJ and U-SDJ powders had a_w values < 0.2 which confirms the efficacy of the freeze-drying process (Table 1). Foods with a a_w<0.6 are typically considered to be microbiologically stable (Quek et al., 2007).

3.3.2. Color

U-SDJ had significantly ($p < 0.05$) higher L* values (perceived lightness) than H-SDJ (Table 1). Meanwhile, H-SDJ had significantly ($p < 0.05$) higher a* (red/green), and b* (blue/yellow) values than U-SDJ (Table 1). The hue angle measures the property of a color based on the ratio of a* and b*, while the chroma indicates the saturation of color intensity (Quek et al., 2007). In Fig. 3., it can be seen that U-SDJ exhibits a brighter white color compared to H-SDJ, which appears more as a light, pale-yellow powder. It has been reported that gelatin from the salted, dried jellyfish *Lobonema smithii*, had an initial light-yellow color, which then appeared darker after a hydrolysis procedure (Lueyot et al., 2020). Rodsuwan et al. (2016) reported that gelatin from the jellyfish *Lobonema smithii* was more orange/yellow in color compared to bovine gelatin. Lueyot et al. (2020) reported the resulting darkening of color may be a consequence of the Maillard reaction during hydrolysis. Although color does not affect the physicochemical properties of gelatin, a more neutral color is preferred, as it will have less of an impact in the final food application (Shyni et al., 2014).

3.3.3. Ash content and mineral profile

The ash content of U-SDJ was significantly ($p < 0.05$) higher than that of H-SDJ (Table 1). This may be due to U-SDJ not undergoing washing and soaking steps to remove excess minerals like in the case of H-SDJ. Besides Na and Al, most of the minerals detected in H-SDJ were present in relatively small quantities (Table 2). The traditional salting process in the production of SDJ employs ~1 kg of NaCl:alum (1:10, w/

Table 3
Particle size distribution of unhydrolyzed salted and dried jellyfish (U-SDJ) and hydrolyzed-SDJ (H-SDJ) powders.[1].

	Units	U-SDJ	H-SDJ
D_{10}	μm	0.57 ± 0.33	0.74 ± 0.02***
D_{50}	μm	1.81 ± 0.02	12.81 ± 1.38***
D_{90}	μm	25.59 ± 0.27	320.1 ± 3.56***
Mean	μm	8.42 ± 0.59	107.0 ± 2.69***
Span	μm	13.77 ± 0.19	25.47 ± 2.69***

[1] Values are means ± standard deviation of triplicate determinations.
***Denote significant difference ($p < 0.001$) between U-SDJ and H-SDJ gelatins.

w) mixture per 8–10 kg of jellyfish, where it is left to brine for ~40 days (Hsieh et al., 2001). Consequently, the ash content (g/100 g d.b.) is high in both U-SDJ (88.53) and H-SDJ (56.61). U-SDJ had significantly ($p < 0.05$) greater Na content than H-SDJ; however, Al, P and S contents were significantly ($p < 0.05$) higher in H-SDJ than in U-SDJ. This suggests that the Al from the salt:alum mixture may have already diffused beneath the jellyfish tissues. Hence, when tested for minerals, there is less Na per known mass of sample but similar quantities of other minerals; thus, the concentration of Al and other minerals appear to increase. While the Na and Al concentrations may appear high, the US Department of Agriculture (USDA) considers SDJ a safe-to-eat food product, and the nutritional information is available on the USDA's FoodData Central (USDA, 2009).

3.3.4. Particle size distribution

U-SDJ had significantly ($p < 0.05$) smaller sized particles than H-SDJ (Table 3). It is believed that the smaller mean particle size of U-SDJ may be due to its higher mineral content. Furthermore, H-SDJ powders had significantly ($p < 0.05$) higher quantities of larger particles (>100 μm) than U-SDJ. Both, U-SDJ and H-SDJ showed agglomerated particles (span values > 2); yet, significantly ($p < 0.05$) greater particle agglomeration was observed in H-SDJ. The increased exposure of proteinaceous surfaces and the formation of irreversible link bridges due to the hydrolysis of the proteins in H-SDJ may have facilitated the particle agglomeration process and the production of larger-sized particles (Tonon et al., 2011). The D_{10} and D_{90} in accordance with the span values show that U-SDJ exhibited significantly ($p < 0.05$) smaller particles than H-SDJ. In the case of U-SDJ, particles <10 μm accounted for ~80% of the total particles compared to only ~50% in H-SDJ (data not shown).

Gelatin powders with different particle sizes are used for different applications. According to "Gelatin mesh size & why it matters", larger/more coarse gelatins (i.e., Mesh #8 or 2380 μm) are used to fabricate soft gels, marshmallows, and gummy treats; whereas smaller/finer gelatins (i.e., Mesh #40 or 400 μm) are used in desserts and other baked products (Anonymous, 2020). Typically, the finer the particle size, the more readily it will dissolve. Modification of particle size is possible by using different means of drying (i.e., freeze or spray drying) as well as adjusting the time and the type of grinder mill utilized.

3.3.5. Microstructure

The three-dimensional characterization of U-SDJ and H-SDJ powders via SEM illustrates similar characteristics of particles that agglomerated into crumb-like groups with a porous structure (Fig. 3A and B). The porous structure may be due to ice crystals and/or air bubbles that occurred during the initial freezing process, evaporation of the water from sublimation, and mechanical stresses caused by inhomogeneous drying during the freeze-drying process (Esfahani et al., 2019). Particle aggregation can occurs when water droplets come close together during the drying process due to water's surface tension properties (Ilyasoglu & El, 2014). These aggregating water droplets contain protein and minerals, thus causing the crumb-like group formations after the water has been removed. It has been reported that gelatin gels with lower concentrations of Ca^{2+} and/or Na^{+} ions had a more uniform/compact structure, smoother surface, and smaller pore size compared to gels that had higher concentrations of these minerals (Wang et al., 2018). Both powders were seen to be amorphous with flat-like shapes, which is hypothesized to be the proteinaceous material covered by the minerals.

3.3.6. Bloom strength

Interestingly, H-SDJ powders successfully produced gelatin gels, unlike U-SDJ powders. Gelatin gels produced with 10% (w/v) H-SDJ powders showed significantly ($p < 0.05$) higher Bloom values than those prepared with 5 and 6.67% (w/v) H-SDJ (Table 1). The Bloom value (g) of gelatin gels prepared from H-SDJ powders at 6.67 and 10% (w/v) concentration were 3.4 and 4.2, respectively (Table 1). Additionally, very weak gelatin gels were produced with H-SDJ powders at 5% (w/v) concentrations. Studies have reported on the Bloom values of mammalian and fish gelatins; for example, eel (*Monopterus* sp.) skin gelatin gels had Bloom values of 213 and 215 g, respectively, while a bovine gelatin gel had a Bloom of 273 g (Nurul & Sarbon, 2015). Gels produced with gelatin from a species of jellyfish (*Lobonema smithii*) had Bloom values between 8.8 and 324 g. It has been reported that Bloom values of jellyfish gelatin are dictated by extraction and production methods (Lueyot et al., 2020; Rodsuwan et al., 2016). In this study, H-SDJ powders gelatinized and yielded weak gelatin gels. These findings are promising and provide potential for improvement as no optimization or modification of the H-SDJ gelatin was performed. Importantly, stronger gels are not necessarily associated with higher gelatin quality; rather, it depends on the specific food application or target functionality that is desired for a product.

The predominant amino acids in the jellyfish *Rhopilema hispidum* are glycine, proline, alanine and hydroxyproline, and the total amount of these amino acids is an important factor in the thermal stability of the resultant gelatin gel (Cho et al., 2014). According to Nagai et al. (1999) and Karim and Bhat (2009), CBJ had an amino acid composition (residues/1000 total amino acid residues) for proline, hydroxyproline, and alanine totaling 204, while for porcine gelatin it was 335. This difference may explain why weaker gels are produced from H-SDJ compared to porcine gelatin. H-SDJ may have different functional properties than traditional mammalian gelatins, which may provide unique characteristics to products when utilizing this gelatin.

3.3.7. Dynamic viscoelastic behavior

3.3.7.1. Temperature sweep. The behaviors of the elastic (storage) (G′) vs the viscous (loss) modulus (G″) of gelatin gels prepared with H-SDJ powders from 5 to 20 °C at 5, 6.67 and 10% (w/v) concentrations are presented in Fig. 4A–C, respectively. According to Sarbon et al. (2015), temperature sweep tests determine the melting temperature (T_m, °C) of gelatin gels. The T_m (tan δ = 1 or crossover of G′ and G″) for gels prepared with H-SDJ powders at 5, 6.67 and 10% (w/v) concentration were approximately 15.47, 15.09, and 16.12 °C, respectively. The T_m of gels were significantly ($p < 0.05$) greater with an increased concentration of H-SDJ powders. Furthermore, gelatin gels prepared with more H-SDJ powder exhibited significantly ($p < 0.05$) higher G′ (Pa) and G″ values (Pa) compared to gels prepared with a lower concentration of H-SDJ powder. This confirms the results for gel strength, which suggest that a greater concentration of H-SDJ powder gives stiffer gels. Also, it was observed that the gels begin deforming at ~11 °C (i.e., significant reduction in gel elasticity or G′ values).

Cho et al. (2014) reported a T_m of 22.3 °C for gelatin gels prepared from the jellyfish *Rhopilema hispidum*. The difference in T_m between the gelatin gels from *Rhopilema hispidum* and H-SDJ may be due to variations in the respective amino acid profiles. For instance, lower quantities of proline and hydroxyproline have been reported to be a factor for lower temperature denaturation of gelatins gels (Karim & Bhat, 2009). Similar quantities of proline have been reported in both CBJ and in *Rhopilema hispidum*, but hydroxyproline quantities (residues/1000 residues) were reported to be 139 in *Rhopilema hispidum* compared to only 40 in CBJ

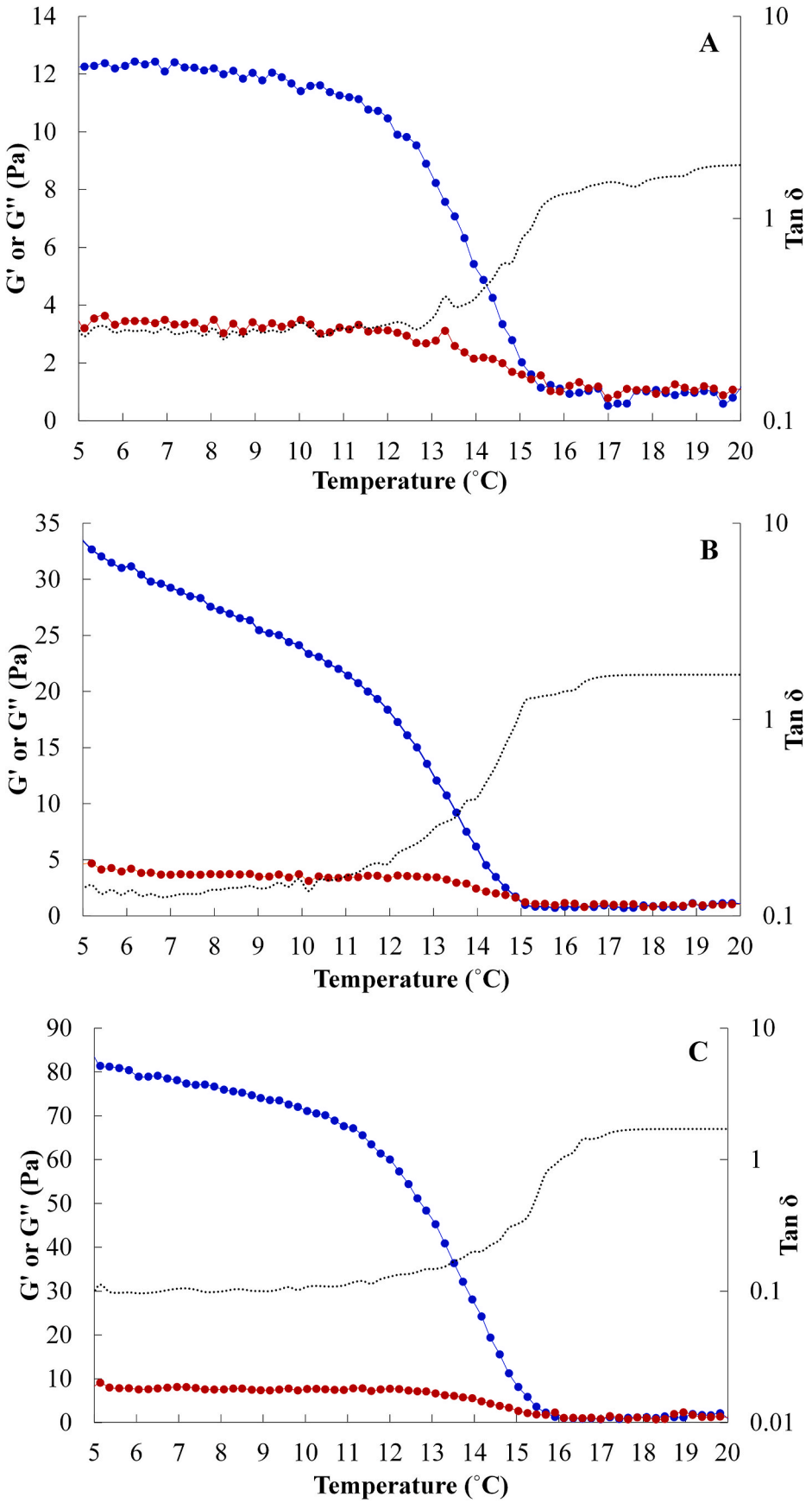

Fig. 4. Temperature sweeps for hydrolyzed salted, dried jellyfish (H-SDJ) powders at concentrations of (A) 5% (w/v);(B) 6.67% (w/v); and (C) 10% (w/v). —●— = G′; —●— = G″; and ••• = Tan δ.

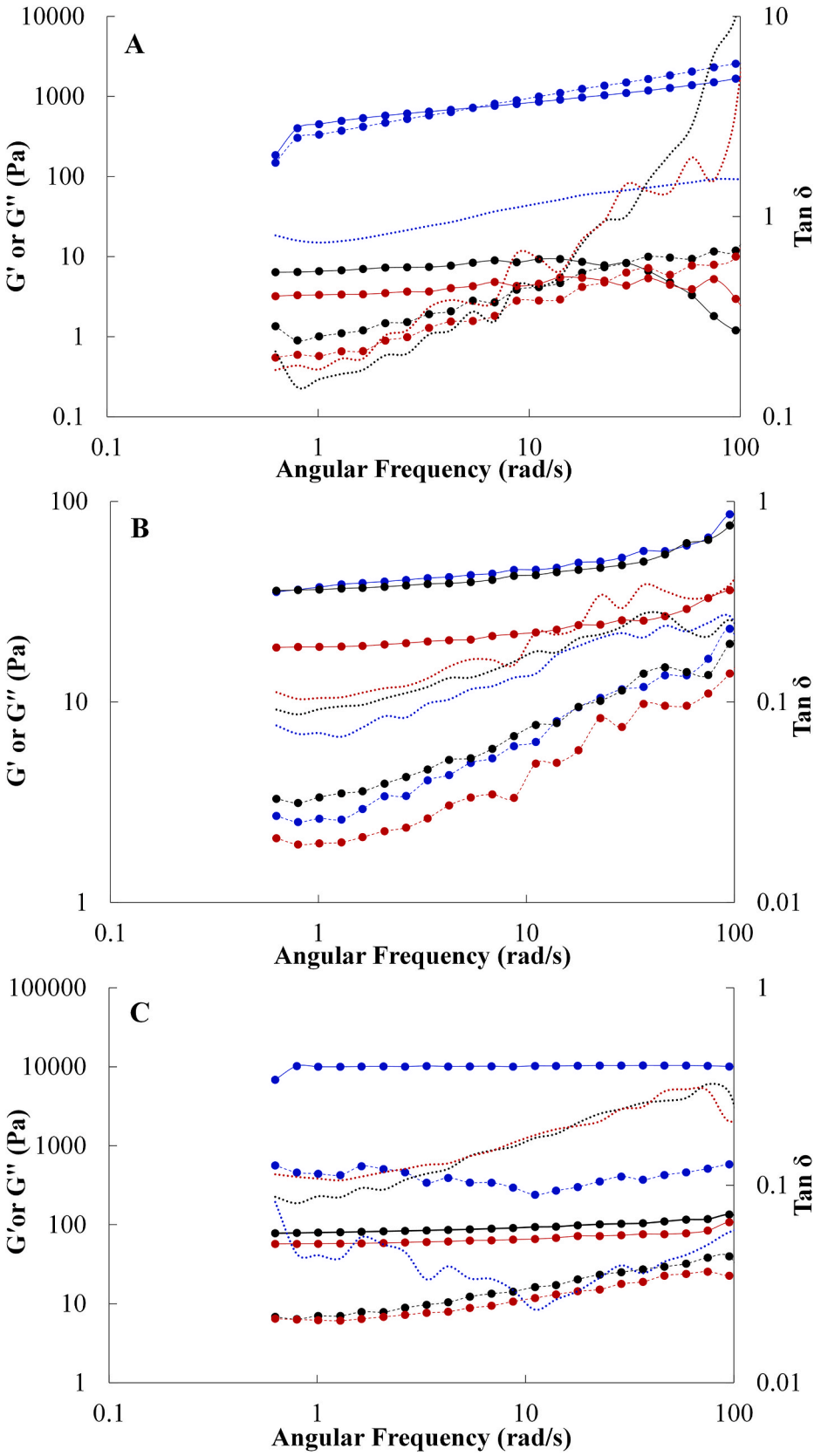

Fig. 5. Frequency sweeps for hydrolyzed salted, dried jellyfish (H-SDJ) powders at concentrations of (A) 5% (w/v); (B) 6.67% (w/v); and (C) 10% (w/v). —●— = G′ (−2 °C); -●- = G″ (−2°C); —●— = G′ (4 °C); -●- = G″ (4 °C); —●— = G′ (10 °C); -●- = G″ (10 °C); ····· = Tan δ (−2 °C); ····· = Tan δ (4 °C); and ····· = Tan δ (10 °C).

Table 4
Herschel-Bulkley flow model parameters for hydrolyzed-SDJ solutions at different solid concentrations (%, w/v) and temperatures[1].

Solid concentration (%, w/v)	Parameter	Temperature		
		−2 °C	4 °C	10 °C
5	τ_o (Pa)	11.79 ± 3.23^{cA}	8.49 ± 1.09^{cB}	9.09 ± 0.90^{bB}
	K (Pa s^n)	13.97 ± 3.21^{cA}	9.85 ± 0.64^{cB}	9.48 ± 0.88^{bB}
	n	0.11 ± 0.03^{aB}	0.16 ± 0.01^{aA}	0.13 ± 0.02^{aAB}
	R^2	0.98	0.95	0.95
6.67	τ_o (Pa)	43.20 ± 4.45^{bA}	25.80 ± 1.10^{bB}	8.95 ± 1.36^{bC}
	K (Pa s^n)	45.42 ± 4.43^{bA}	27.27 ± 1.22^{bB}	9.17 ± 1.30^{bC}
	n	0.08 ± 0.01^{aB}	0.13 ± 0.01^{bA}	0.08 ± 0.02^{bB}
	R^2	0.96	0.95	0.96
10	τ_o (Pa)	58.93 ± 4.73^{aA}	56.94 ± 7.20^{aA}	28.43 ± 0.05^{aB}
	K (Pa s^n)	63.90 ± 7.64^{aA}	58.54 ± 7.18^{aB}	29.45 ± 0.30^{aC}
	n	0.11 ± 0.00^{aB}	0.13 ± 0.02^{abA}	0.16 ± 0.02^{aA}
	R^2	0.95	0.95	0.95

abc Means with different letters in the same column are significantly different ($p < 0.05$).
ABC Means with different letters in the same row are significantly different ($p < 0.05$).
[1] Values are means ± standard deviation of triplicate determinations.

(Cho et al., 2014; Nagai et al., 1999). The low T_m of H-SDJ gelatin gels may be beneficial in specific/targeted food applications (i.e., melt-in-mouth feel).

3.3.7.2. Frequency sweep. Frequency sweeps determine the effect of colloidal/intrinsic forces during a sweep of oscillatory frequencies with a constant oscillation amplitude and temperature (Franck, 2021, pp. 1–11). Frequency sweeps help identify the rheological behavior of materials during storage and in applications (Sarbon et al., 2015). Gelatin gels prepared at a 5% (w/v) H-SDJ powder concentration were frequency dependent regardless of the evaluated temperature (Fig. 5A). Meanwhile, gelatin gels prepared with 6.67 and 10% H-SDJ powder concentrations were independent of the frequency at each of the evaluated temperatures examined (Fig. 5B and C). According to Sarbon et al. (2015), weak and entangled gel networks are frequency dependent; meanwhile, covalent and strong gels are independent of frequency. In the case of gelatin gels prepared at 6.67 and 10% H-SDJ concentration, their G′>G″ was seemingly independent of the applied frequency, which thereby indicates that the products behaved more gel-like compared to a more fluid-like behavior (Franck, 2021, pp. 1–11). A recent study demonstrated how increasing Ca^{2+} ions produced more egg-box junctions, which resulted in G′>G″ in all tested samples (Muñoz-Almagro et al., 2021). In Fig. 5A–C, as frequency increased with lower temperatures, more stability was observed as concentration increased from 5 to 10% (w/v). It has been reported that higher temperatures and lower solid concentrations reduce internal friction in gelatin gels due to a reduced number of collisions between molecules (Qiu et al., 2018).

Additionally, tan δ (G″/G′) compares the relative strength between the gels viscous and elasticity tendencies of the sample (Dai et al., 2020). Generally, strong gels with a more solid-like nature have a tan δ value < 0.1 (Sarbon et al., 2015). At lower frequencies, gelatin gels prepared with 6.67 and 10% H-SDJ powder concentration had significantly ($p < 0.05$) lower tan δ values (~0.1) than those gels prepared at 5% H-SDJ. Tan δ increased at higher frequencies but always remained under 1.0, indicating elastic tendencies. This suggests that the H-SDJ gels have more elastic properties between the angular frequencies of 1–100 (rad/s), and confirm that this process was effective to yield jellyfish gelatins with gelling properties from SDJ.

3.3.7.3. Flow properties. Rheological properties, including yield stress (τ_0), consistency index (K), and flow behavior (n) of H-SDJ gelatin solutions prepared at 5, 6.67, and 10% (w/v) concentrations as a function of temperature (−2, 4, and 10 °C) are listed in Table 4. A non-Newtonian, shear-thinning behavior ($n < 1$) was observed in all gelatin solutions. The results also indicated that gelatin solutions behaved as Herschel-Bulkley liquids ($n < 1$ with $\tau_0 > 0$). The Herschel-Bulkley flow model was suitable for predicting the flow behavior of the gelatin gels (denoted by $R^2 \geq 0.95$) and has been used to characterize the flow behavior of marine gelatin gels (Chandra & Shamasundar, 2015; Huang et al., 2019). A significant ($p < 0.05$) reduction in the viscosity of gelatin gels observed at higher shear rates may be due to the breakdown of the gel network and microstructures. The values for yield stress and consistency index were significantly ($p < 0.05$) greater in gelatin gels prepared at higher H-SDJ powder concentrations and lower temperatures. Yield stress accounts for the initial pressure to initiate deformation, and larger values may indicate greater intramolecular attractions (Muhoza et al., 2019). Meanwhile, a higher consistency index is associated with better gel structures due to an increased viscosity that results from the restriction of molecular motion of peptides (Derkach et al., 2015). These findings are in agreement with those reported by Chandra and Shamasundar (2015), who indicated that yield stress and consistency index of fish gelatin gels are both concentration- and temperature-dependent.

The effect of temperature on the apparent viscosity (measured at a shear rate of 100 s^{-1}) of gelatin gels is presented in Fig. 6. The apparent viscosities of gelatin gels prepared at 5, 6.67, and 10% concentration (w/v) H-SDJ at −2 °C were ~400, 800 and 1500 mPa s, respectively. Significantly ($p < 0.05$) greater apparent viscosities were observed in

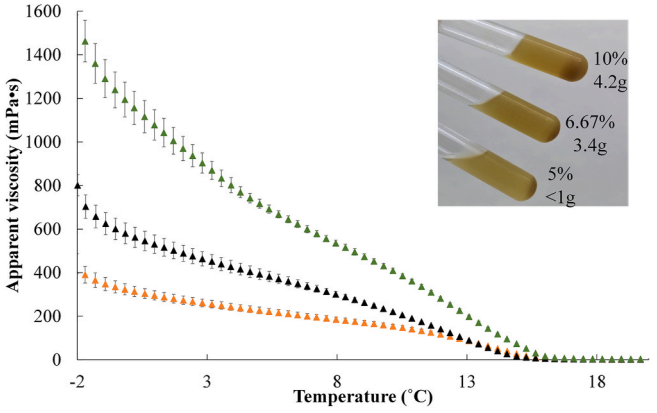

Fig. 6. Apparent viscosity changes at differing temperatures for hydrolyzed salted, dried jellyfish (H-SDJ) powders in solution at concentrations of ▲ 10% (w/v); ▲ 6.67% (w/v); and ▲ 5% (w/v). The inserted image depicts gelatin gels prepared at different H-SDJ concentrations maturated at 10 °C with their corresponding Bloom value in grams (g). [1]Value with < symbol were below the detection limit of the TA.XT texture analyzer.

gelatin gels prepared at higher concentrations of H-SDJ from −2 to 15 °C. As temperature increased, the apparent viscosity of gelatin gels significantly ($p < 0.05$) decreased and approached 0 mPa s at 15 °C for each concentration upon melting, which signifies no thickening capability even at high concentrations above the melting temperature. The inserted image in Fig. 6 illustrates 5, 6.67, and 10% (w/v) concentrations of H-SDJ formed at 10 °C, which demonstrates that at low concentration (5%) there was minimal gel formation and gelation increased as concentration increased. Overall, this data correlates with the Bloom strength and rheological tests performed, which demonstrates that improved gelation occurs with H-SDJ at higher concentrations (≥6.67%, w/v).

As previously stated, CBJ is an emerging fishery on the Atlantic coast of the USA. To date, the only commercial product of the US jellyfish industry is SDJ (i.e., a niche product for Asian markets) with a retail value ~2–4 USD per kilo in the USA. According to Esther et al. (2021), the US jellyfish industry is still artisanal with great potential for future growth. It has been estimated that the maximum catch potential of CBJ will significantly increase in the next thirty years (Cisneros-Mata et al., 2019). For long-term viability and acceptance in Western markets, the US jellyfish industry will require food innovation and the introduction of novel jellyfish-based foods and ingredients. Undoubtedly, food innovation has played a critical role in driving economic growth and prosperity of the modern food industry. Research has suggested that the global climate is changing and CBJ will readily adapt; therefore, the opportunity has been presented to create a fledging industry of jellyfish-based products in the USA. Hence, this study may assist in the capitalization of opportunities presented by the current market regarding novel food trends and will help showcase the full potential of the US jellyfish industry.

4. Conclusion

This study illustrates (for the first time) the feasibility of utilizing Georgia-caught salted, dried cannonball jellyfish as a source of collagen-rich material to produce novel marine gelatin powders with gelling properties. This research produced a promising food ingredient using a safe, simple, and effective hydrolysis procedure. Gelatin powders from salted, dried cannonball jellyfish were able to produce gels whereas the unhydrolyzed jellyfish powders did not have any gelling properties. The rheological data collected demonstrates unique functional properties for the resultant jellyfish powders. With the search for environmentally friendly/sustainable food sources, using nontraditional sources, like cannonball jellyfish, is the beginning of a unique area of food innovation, which seeks to produce a useable food ingredient from an unlikely source that is virtually unknown in Western societies with a broad range of potential applications.

CRediT authorship contribution statement

Peter G. Chiarelli: Conceptualization, Methodology, Investigation, Writing – original draft. **Ronald B. Pegg:** Conceptualization, Methodology, Writing – review & editing. **Govindaraj Dev Kumar:** Formal analysis, Writing – review & editing, Data curation. **Kevin Mis Solval:** Conceptualization, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors reported no conflict of interest in this research.

Acknowledgments

This project was financially supported by the Georgia Sea Grant Research Traineeship program and the USDA's National Institute of Food and Agriculture - Foundational Program Award #2021-67017-33442.

References

Anonymous. (1996). US-EPA method 3052: Microwave assisted acid digestion of siliceous and organically based matrices. In *Test methods for evaluating solid waste* (3rd ed.). Washington, DC: US Environmental Protection Agency. Revision 0. Retrieved September 10, 2021, from https://www.epa.gov/sites/production/files/2015-12/documents/3052.pdf.

Anonymous. (2020). Gelatin mesh size & why it matters. Retrieved September 10, 2021, from https://www.customcollagen.com/gelatin-mesh-size-why-it-matters/.

Aoac. (2019). *Official methods of analysis* (21st ed.). AOAC International.

Borza, A. D., Annan, N. T., Moreau, D. L., Allan-Wojtas, P. M., Ghanem, A., Rousseau, D., & Hansen, L. T. (2010). Microencapsulation in genipin cross-linked gelatine-maltodextrin improves survival of *Bifidobacterium adolescentis* during exposure to *in vitro* gastrointestinal conditions. *Journal of Microencapsulation, 27*, 387–399.

Boudhrioua, N., Djendoubi, N., Bellagha, S., & Kechaou, N. (2009). Study of moisture and salt transfers during salting of sardine fillets. *Journal of Food Engineering, 94*, 83–89.

Brotz, L., Cheung, W. W. L., Kleisner, K., Pakhomov, E., & Pauly, D. (2012). Increasing jellyfish populations: Trends in large marine ecosystems. *Hydrobiologia, 690*, 3–20.

Chancharern, P., Laohakunjit, N., Kerdchoechuen, O., & Thumthanaruk, B. (2016). Extraction of type A and type B gelatin from jellyfish (*Lobonema smithii*). *International Food Research Journal, 23*, 419–424.

Chandra, M. V., & Shamasundar, B. A. (2015). Rheological properties of gelatin prepared from the swim bladders of freshwater fish *Catla catla*. *Food Hydrocolloids, 48*, 47–54.

Chang, H.-J., Wang, Q., Zhou, G.-H., Xu, X.-L., & Li, C.-B. (2010). Influence of weak organic acids and sodium chloride marination on characteristics of connective tissue collagen and textural properties of beef semitendinosus muscle. *Journal of Texture Studies, 41*, 279–301.

Cho, S., Ahn, J.-R., Koo, J.-S., & Kim, S.-B. (2014). Physicochemical properties of gelatin from jellyfish *Rhopilema hispidum*. *Fisheries and Aquatic Sciences, 17*, 299–304.

Cisneros-Mata, M. A., Mangin, T., Bone, J., Rodriguez, L., Smith, S. L., & Gaines, S. D. (2019). Fisheries governance in the face of climate change: Assessment of policy reform implications for Mexican fisheries. *PLoS One, 14*, Article e0222317.

Creed, J. T., Brockhoff, C. A., & Martin, T. D. (1994). US-EPA method 200.8: Determination of trace elements in waters and wastes by inductively coupled plasma-mass spectrometry. In *Environmental monitoring Systems laboratory office of research and development, revision 5.4 EMMC version*. Cincinnati, OH: US Environmental Protection Agency.

Dai, H., Li, X., Du, J., Ma, L., Yu, Y., Zhou, H., … Zhang, Y. (2020). Effect of interaction between sorbitol and gelatin on gelatin properties and its mechanism under different citric acid concentrations. *Food Hydrocolloids, 101*, 105557.

Derkach, S. R., Ilyin, S. O., Maklakova, A. A., Kulichikhin, V. G., & Malkin, A. Y. (2015). The rheology of gelatin hydrogels modified by κ-carrageenan. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 63*, 612–619.

Duarte, C. M., Pitt, K. A., Lucas, C. H., Purcell, J. E., Uye, S.-i., Robinson, K., … Condon, R. H. (2013). Is global ocean sprawl a cause of jellyfish blooms? *Frontiers in Ecology and the Environment, 11*, 91–97.

Esfahani, R., Jafari, S. M., Jafarpour, A., & Dehnad, D. (2019). Loading of fish oil into nanocarriers prepared through gelatin-gum Arabic complexation. *Food Hydrocolloids, 90*, 291–298.

Esther, C. C. M., Ángel, C. M. M., Gabriela, M. M., Ileana, E., Miguel, C. M. A., & Luis, M. C. (2021). Analysis of the Gulf of California cannonball jellyfish fishery as a complex system. *Ocean & Coastal Management, 207*, 105610.

Fluech, B. (2018). *Georgia's jellyball industry*. Retrieved September 10, 2021, from https://gacoast.uga.edu/wp-content/uploads/2019/03/1809-Fisheries-Deliverables-Jellyball-Flyer-FINAL.pdf.

Franck, A. (2021). *Understanding rheology of structured fluids*. Retrieved September 10, 2021, from http://www.tainstruments.com/pdf/literature/AAN016_V1_U_StructFluids.pdf.

Future of Food Report. (2019). Retrieved September 10, 2021, from https://www.about.sainsburys.co.uk/~/media/Files/S/Sainsburys/pdf-downloads/futureoffood-10c.pdf.

Gmia. (2019). *Standard testing methods for edible gelatin*. Gelatin Manufacturers Institute of America. Retrieved September 10, 2021, from http://www.gelatin-gmia.com/uploads/1/1/8/4/118450438/gmia_official_methods_2019.pdf.

Hsieh, Y.-H. P., Leong, F.-M., & Rudloe, J. (2001). Jellyfish as food. *Hydrobiologia, 451*, 11–17.

Huang, T., Tu, Z.-C., Shangguan, X., Sha, X., Wang, H., Zhang, L., & Bansal, N. (2019). Fish gelatin modifications: A comprehensive review. *Trends in Food Science & Technology, 86*, 260–269.

Ilyasoglu, H., & El, S. N. (2014). Nanoencapsulation of EPA/DHA with sodium caseinate–gum Arabic complex and its usage in the enrichment of fruit juice. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 56*, 461–468.

Jiang, N., Dev Kumar, G., Chen, J., Mishra, A., & Mis Solval, K. (2020). Comparison of concurrent and mixed-flow spray drying on viability, growth kinetics and biofilm formation of *Lactobacillus rhamnosus* GG microencapsulated with fish gelatin and maltodextrin. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 124*, 109200.

Jung, S., Rickert, D. A., Deak, N. A., Aldin, E. D., Recknor, J., Johnson, L. A., & Murphy, P. A. (2003). Comparison of Kjeldahl and Dumas methods for determining protein contents of soybean products. *Journal of the American Oil Chemists' Society, 80*, 1169–1173.

Karim, A. A., & Bhat, R. (2009). Fish gelatin: Properties, challenges, and prospects as an alternative to mammalian gelatins. *Food Hydrocolloids, 23*, 563–576.

Khong, N. M. H., Yusoff, F. M., Jamilah, B., Basri, M., Maznah, I., Chan, K. W., & Nishikawa, J. (2016). Nutritional composition and total collagen content of three commercially important edible jellyfish. *Food Chemistry, 196*, 953–960.

Leone, A., Lecci, R. M., Durante, M., Meli, F., & Piraino, S. (2015). The bright side of gelatinous blooms: Nutraceutical value and antioxidant properties of three Mediterranean jellyfish (*Scyphozoa*). *Marine Drugs, 13*, 4654–4681.

Leone, A., Lecci, R. M., Milisenda, G., & Piraino, S. (2019). Mediterranean jellyfish as novel food: Effects of thermal processing on antioxidant, phenolic, and protein contents. *European Food Research and Technology, 245*, 1611–1627.

Li, X. Y., Chen, X. G., Cha, D. S., Park, H. J., & Liu, C. S. (2009). Microencapsulation of a probiotic bacteria with alginate–gelatin and its properties. *Journal of Microencapsulation, 26*, 315–324.

Lueyot, A., Rungsardthong, V., Vatanyoopaisarn, S., Hutangura, P., Wongsa-Ngasri, P., Roytrakul, S., & Thumthanaruk, B. (2020). Improved physicochemical properties of type A gelatin from by-products salted jellyfish *(Lobonema smithii)* by optimized pretreatment and extraction conditions. *Research Square*. https://doi.org/10.21203/rs.3.rs-62849/v1

Mis Solval, K., Bankston, J. D., Bechtel, P. J., & Sathivel, S. (2016). Physicochemical properties of microencapsulated ω-3 salmon oil with egg white powder. *Journal of Food Science, 81*, E600–E609.

Muhoza, B., Xia, S., & Zhang, X. (2019). Gelatin and high methyl pectin coacervates crosslinked with tannic acid: The characterization, rheological properties, and application for peppermint oil microencapsulation. *Food Hydrocolloids, 97*, 105174.

Muñoz-Almagro, N., Villamiel, M., Wilde, P. J., Gunning, A. P., & Montilla, A. (2021). Effect of sucrose substitution with stevia and saccharin on rheological properties of gels from sunflower pectins. *Food Hydrocolloids, 120*, 106910.

Nagai, T., Ogawa, T., Nakamura, T., Ito, T., Nakagawa, H., Fujiki, K., … Yano, T. (1999). Collagen of edible jellyfish exumbrella. *Journal of the Science of Food and Agriculture, 79*, 855–858.

Nielsen, P. M., Petersen, D., & Dambmann, C. (2001). Improved method for determining food protein degree of hydrolysis. *Journal of Food Science, 66*, 642–646.

Niu, L., Zhou, X., Yuan, C., Bai, Y., Lai, K., Yang, F., & Huang, Y. (2013). Characterization of tilapia (*Oreochromis niloticus*) skin gelatin extracted with alkaline and different acid pretreatments. *Food Hydrocolloids, 33*, 336–341.

Nurilmala, M., Hizbullah, H. H., Karnia, E., Kusumaningtyas, E., & Ochiai, Y. (2020). Characterization and antioxidant activity of collagen, gelatin, and the derived peptides from yellowfin tuna (*Thunnus albacares*) skin. *Marine Drugs, 18*, 98.

Nurul, A. G., & Sarbon, N. M. (2015). Effects of pH on functional, rheological and structural properties of eel (*Monopterus* sp.) skin gelatin compared to bovine gelatin. *International Food Research Journal, 22*, 572–583.

Patwa, A., Thiéry, A., Lombard, F., Lilley, M. K. S., Boisset, C., Bramard, J.-F., … Barthélémy, P. (2015). Accumulation of nanoparticles in "jellyfish" mucus: A bio-inspired route to decontamination of nano-waste. *Scientific Reports, 5*, 11387.

Qiu, L., Shen, Y., Wang, T., & Wang, C. (2018). Rheological and fracturing characteristics of a novel sulfonated hydroxypropyl guar gum. *International Journal of Biological Macromolecules, 117*, 974–982.

Quek, S. Y., Chok, N. K., & Swedlund, P. (2007). The physicochemical properties of spray-dried watermelon powders. *Chemical Engineering and Processing, 46*, 386–392.

Rahman, M. S., Al-Saidi, G. S., & Guizani, N. (2008). Thermal characterisation of gelatin extracted from yellowfin tuna skin and commercial mammalian gelatin. *Food Chemistry, 108*, 472–481.

Rodsuwan, U., Thumthanaruk, B., Kerdchoechuen, O., & Laohakunjit, N. (2016). Functional properties of type A gelatin from jellyfish (*Lobonema smithii*). *International Food Research Journal, 23*, 507–514.

Roslan, J., Mustapa Kamal, S. M., Yunos, K. F. M.d., & Abdullah, N. (2015). Optimization of enzymatic hydrolysis of tilapia (*Oreochromis niloticus*) by-product using response surface methodology. *International Food Research Journal, 22*, 1117–1123.

Sarbon, N. M., Badii, F., & Howell, N. K. (2015). The effect of chicken skin gelatin and whey protein interactions on rheological and thermal properties. *Food Hydrocolloids, 45*, 83–92.

Senphan, T., & Benjakul, S. (2014). Antioxidative activities of hydrolysates from seabass skin prepared using protease from hepatopancreas of Pacific white shrimp. *Journal of Functional Foods, 6*, 147–156.

Shahidi, F., Han, X.-Q., & Synowiecki, J. (1995). Production and characteristics of protein hydrolysates from capelin (*Mallotus villosus*). *Food Chemistry, 53*, 285–293.

Shyni, K., Hema, G. S., Ninan, G., Mathew, S., Joshy, C. G., & Lakshmanan, P. T. (2014). Isolation and characterization of gelatin from the skins of skipjack tuna (*Katsuwonus pelamis*), dog shark (*Scoliodon sorrakowah*), and rohu (*Labeo rohita*). *Food Hydrocolloids, 39*, 68–76.

Solval, K. M., Sundararajan, S., Alfaro, L., & Sathivel, S. (2012). Development of cantaloupe (*Cucumis melo*) juice powders using spray drying technology. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 46*(1), 287–293.

Tonon, R. V., Grosso, C. R. F., & Hubinger, M. D. (2011). Influence of emulsion composition and inlet air temperature on the microencapsulation of flaxseed oil by spray drying. *Food Research International, 44*, 282–289.

USDA. (2009). *Jellyfish, dried, salted*. Retrieved September 10, 2021, from https://fdc.nal.usda.gov/fdc-app.html#/food-details/168129/nutrients.

Wang, W., Shen, M., Liu, S., Jiang, L., Song, Q., & Xie, J. (2018). Gel properties and interactions of *Mesona blumes* polysaccharide-soy protein isolates mixed gel: The effect of salt addition. *Carbohydrate Polymers, 192*, 193–201.

Wisuthiphaet, N., Kongruang, S., & Chamcheun, C. (2015). Production of fish protein hydrolysates by acid and enzymatic hydrolysis. *Journal of Medical and Bioengineering, 4*, 466–470.

Zhuang, Y.-L., Sun, L.-P., Zhao, X., Hou, H., & Li, B.-F. (2010). Investigation of gelatin polypeptides of jellyfish (*Rhopilema esculentum*) for their antioxidant activity *in vitro*. *Food Technology and Biotechnology, 48*, 222–228.

Zhuang, Y., Sun, L., Zhao, X., Wang, J., Hou, H., & Li, B. (2009). Antioxidant and melanogenesis-inhibitory activities of collagen peptide from jellyfish (*Rhopilema esculentum*). *Journal of the Science of Food and Agriculture, 89*, 1722–1727.

Zhu, J., Wang, X., He, C., & Wang, H. (2012). Mechanical properties, anisotropic swelling behaviours and structures of jellyfish mesogloea. *Journal of the Mechanical Behavior of Biomedical Materials, 6*, 63–73.