


Review

Production of Fish Analogues from Plant Proteins: Potential Strategies, Challenges, and Outlook

Chengxuan Zhong ¹, Yiming Feng ^{2,*} and Yixiang Xu ^{3,*}

¹ Department of Agrotechnology and Food Science, Wageningen University & Research, 6708 PB Wageningen, The Netherlands

² Department of Food Science & Nutrition, California Polytechnic State University, San Luis Obispo, CA 93407, USA

³ Healthy Processed Foods Research Unit, Western Regional Research Center, USDA-ARS 800 Buchanan Street, Albany, CA 94710, USA

* Correspondence: yfeng06@calpoly.edu (Y.F.); yixiang.xu@usda.gov (Y.X.)

Abstract: Fish products are consumed by human beings as a high-quality protein source. However, overfishing, and pollution puts out an urgent call to seek a new strategy to substitute fish protein for secure eco-sustainability. Plant-based fish analogs, which mimic the structure, texture, and flavor of fish meat products, are a rapid-growing segment of the food products. The purpose of this review is to discuss the feasibility and potential strategies for developing plant-based fish analog. The nutritional properties, especially the protein quality of plant-based fish analogs, were discussed. Furthermore, a thorough comparison was made between fish and terrestrial animal muscle structures, including both macroscopical and microscopical structures. Potential processing technologies for producing plant-based fish analogs from plant proteins and approaches for the characterization of the fish analog structures were elaborated. Comparing all the current processing techniques, extrusion is the predominately used technique in the current industry. At the same time, 3D-printing and electrospinning have shown the prominent potential of mimicking fish muscle structure as bottom-up approaches. Finally, key challenges and future research were discussed for the potential commercialization of plant-based fish analogues. The primary focus of this review covers the innovative works that were indexed in the Web of Science Core Collection in the past five years.

Keywords: fish analogue; fish meat structure; plant protein; processing; sustainability



Citation: Zhong, C.; Feng, Y.; Xu, Y. Production of Fish Analogues from Plant Proteins: Potential Strategies, Challenges, and Outlook. *Foods* **2023**, *12*, 614. <https://doi.org/10.3390/foods12030614>

Academic Editor: Jose Angel Perez-Alvarez

Received: 2 January 2023

Revised: 23 January 2023

Accepted: 29 January 2023

Published: 1 February 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Present Global Seafood Production

According to the most recent data from the World Bank, the world population has increased more than twice in the past half century [1]. As one of the most important sources of high-quality protein, the demand for fish has increased drastically to meet the needs of the growing population. In the meanwhile, the average consumption per capita of fish has doubled in the past few decades, which in turn requires a fourfold increase in fish production [2]. Although fishery provides an important protein source for human being's consumption, increasingly demanding fish will result in uncontrolled fishery or overfishing, and it will eventually surpass the rate of natural replenishment [3]. Over the past century, the number of the overfished region increased by two-fold globally, making one-third of the total world's fisheries over biological limits [3]. According to the FAO, the recent increase in fish and seafood production, driven by aquaculture, made the capture fisheries reach a bottleneck in the early 1990s [4]. Furthermore, the current aquaculture practice also faces a few challenges, including (1) disruption of the marine ecosystem. For example, pelagic fish, commonly used as feeds, not only threaten the marine ecosystem, but also impede the growth of wild capture fisheries indirectly [5]. (2) Chemical use in aquaculture: antibiotics and pesticides, which are frequently used

for disease management [6], will pollute the environment and impair human health if discharged into external water bodies [7]. (3) Effluent treatment: effluent that is generated during the culturing processes could also pose a huge threat to the environment. A recent study found that dissolved chemicals are more recalcitrant to degradation, and yet more cost-efficient treatments are still underway [7]. Therefore, aquaculture activities may lead to organic waste and toxic compound pollution, which post negative effects on the ambient aquatic ecosystem and reduce the productivity of the aquaculture [8]. In addition, other aquaculture-related pollution, such as plastic pollution or sunk fishing equipment, could also endanger the marine ecosystem [9].

Overfishing has multiple adverse effects on the ocean ecosystem, including an irreversible decline in fish stocks, maturation, and reproduction (e.g., bluefin tuna, Grand Banks cod) [3]. Several fishing strategies have been proposed and applied to prevent overfishing. For example, Individual Tradable Quotas (ITQs) are used to define the total allowable catch per boat, which aim to promote both higher profits for fishermen as well as relieving the pressure of the environmental ecosystem [10]. In the meanwhile, it is urgent for scientists to search for other alternative ways to alleviate the exploitation of the ocean ecosystem and secure sustainable growth. As a more sustainable solution shown in Figure 1, the plant-based fish analogue is proposed to tackle the ecological challenge. There have been many companies that successfully launched plant-based meat products on the market. However, to the best of the author's knowledge, most of those products are meat analogues, while none have been found with fish analogues. Beyond Meat® is known for their plant-based burger and minced meat, which is produced from soy protein and other plant proteins. Other startup companies also produce plant-based products with a great variety, such as the plant-based escalope and meatballs by Vegetarian Butcher® and lupine-based egg pulp by Plan B®. With the rapidly diversifying categories of plant-based product innovation, it is anticipated that plant-based fish analogues will become trending in the near future. However, there is still a knowledge and technological gap to fill. Based on the existing research on meat analogues, the emulation of real fish fillet texture is difficult. Therefore, a comprehensive review of fish composition and structure is presented to reveal possible ways to mimic fish fillets at a micro-scale.

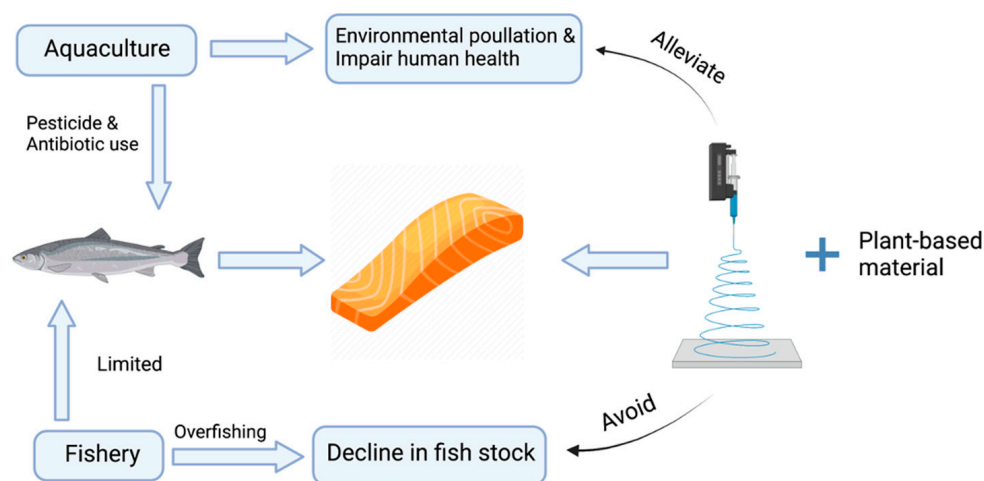


Figure 1. Rationale for developing plant-based fish analogues and the negative impact of fishery and aquaculture.

2. Major Composition of Fish

Fish is an aquatic organism with a great variety of species, and its chemical composition remarkably varies with different species. Water, protein, and fat account for up to 98% of the fish weight, and the weight ratio of major components depends on the fish species [8]. Tuna, cod, and salmon are recognized as the three major fish on the market [11] (Table 1).

Table 1. Moisture, protein, and fat content of selected fish samples.

Fish	Moisture (%)	Protein (%)	Fat (%)	References
Cod, Atlantic (<i>Gadus morhua</i>)	80.8	18.2	0.11	[12]
Atlantic salmon (<i>Salmo salar</i>)	65.6	19.6	14.4	[13]
Tuna, yellowfin (<i>Thunnus albacares</i>)	70.3–72.7	21.8–25.1	3.1–5.7	[14]
Tuna, skipjack (<i>Katsuwonus pelamis</i>)	66.5–72.3	20.72–27.98	3.47–5.73	[14]

2.1. Protein Composition

Muscle tissues take up more than half of total fish weight, and protein accounts for 16–21% of the major constituents [15]. The content of carbohydrates is relatively low, only comprising about 0.5% of the fish muscle [15]. There are three main groups of protein in fish muscle based on their solubility [16]: myofibrillar protein, sarcoplasmic protein, and stroma protein. Myofibrillar proteins, soluble in a concentrated salt solution, are the predominant group of proteins in fish muscle and account for 66–77% of the total mass of fish muscle protein. They consist mainly of myosin, actin, and other proteins, such as troponin and actinin, and can be classified as regulatory proteins and work as structural proteins [17]. Sarcoplasmic proteins, the second-largest group of proteins and the most soluble fraction in fish muscle, constitute 20 to 25% of the total fish muscle proteins [16]: they are a group of proteins that combine several water-soluble and low molecular weight proteins, such as albumins, myoglobin, hemoglobin, and enzymes [16]. Stroma proteins, including collagen and elastin, constitute connective tissue in fish muscle and are completely water insoluble [15,17].

2.2. Protein Quality

Protein Digestibility-Corrected Amino Score (PDCAAS), a rapid and routine method to determine protein quality, assesses the digestibility and amino acid score of a protein sample. PDCAAS is calculated as digestibility ($\times = \text{mg of first limiting amino acid in 1 g of test protein} / \text{mg of the same amino acid in 1 g reference protein} \times 100\%$) [18]. PDCAAS values vary from 0 to 100%, and any value higher than 100% will be truncated to 100% [18]. As plant-based proteins are gaining increasing attention from the public, it is important to evaluate their protein quality to ensure that the nutritional properties of plant-based proteins are comparable to that of fish proteins. PDCAAS for some common plant and animal proteins are shown in Table 2.

PDCAAS of fish protein: Studies have shown that raw marine and freshwater fishes both have a high PDCAAS, which is affected negatively by different processing techniques [19,20]. For instance, broiling and smoking could lower the PDCAAS of rainbow trout [19]. Other common marine fish species, such as salmon, trout, and herring, all have PDCAAS of 1 after truncation [20]. A study of PDCAAS on some freshwater fish species found very high PDCAAS values [21].

PDCAAS of plant proteins: Many plants are known as good sources of proteins, including chickpeas, rice, lentils, and almonds. Soybean, one of the most common plants-protein sources for producing meat analogues, has a PDCAAS of 95% to 102% when untruncated depending on testing methods and soybean sources, mostly at a value of 100% after truncation [22,23]. Some plant protein sources have a slightly poorer PDCAAS, such as wheat, peas, and corn grain at levels of 46.3%, 78.2%, and 47.3%, respectively [22]. Soy protein, as a common source for plant-based meat, contains a relatively low methionine fraction, while many other plant-based proteins are rich in sulfur-containing amino acids [24,25]. Therefore, it could be a feasible solution to blend various plant proteins to increase their amino acid score by complementing limiting amino acids [24]. However, there are other factors that could limit the digestibility of plant protein, such as the antinutritional factors (e.g., Trypsin inhibitors in beans) found within many plants' protein sources [24].

As shown in Table 2, soybean protein has a PDCAAS of 1 after truncation [23], which suggests that the amino acid composition of plant protein is not considered a limiting factor. However, the presence of anti-nutritional compounds in the plant protein could limit the

bioavailability of protein, but they can be inactivated by procedures such as heat treatment and irradiation [26]. When comparing PDCAAS between fish and plant proteins, most fish species were found to have a higher untruncated PDCAAS value. However, it is a worthy note that one protein source with PDCAAS over 1 does not indicate that it is superior to its counterpart having PDCAAS at 1 if it is the sole source of protein in the diet [24]. It means that after truncation, fish protein PDCAAS does not show a superior characteristic to that of soy protein. As a result, the nutritional properties (PDCAAS) should not be considered a drawback when using plant-based protein for manufacturing fish fillet analogs.

Table 2. PDCAAS (Protein Digestibility-Corrected Amino Score) for some typical animal and plant proteins.

Product Type	PDCAAS (after Truncation)	Reference
Cod	0.96	[27]
Tuna	0.97	[28]
Salmon	1	[20]
Herring	1	[20]
Mackerel	1	[20]
Trout	0.998	[19]
Beef	1	[22]
Casein	0.99	[28]
Soy protein	1	[23]
Chickpea protein	0.66	[28]
Lentils	0.52	[28]
Kidney beans	0.68	[28]

3. Fish Muscle Structure

To process plant-protein based fish analogue, it is firstly important to understand the natural structure of fish muscle. In fact, fish muscle presents a highly hierarchical structure, ranging from centimeters to nanometers (shown in Figure 2). Such a hierarchical structure is associated with the unique texture, viscoelastic properties, and mouthfeel of fish products. This section aims to provide a detailed introduction to the fish muscle structure and alignment.

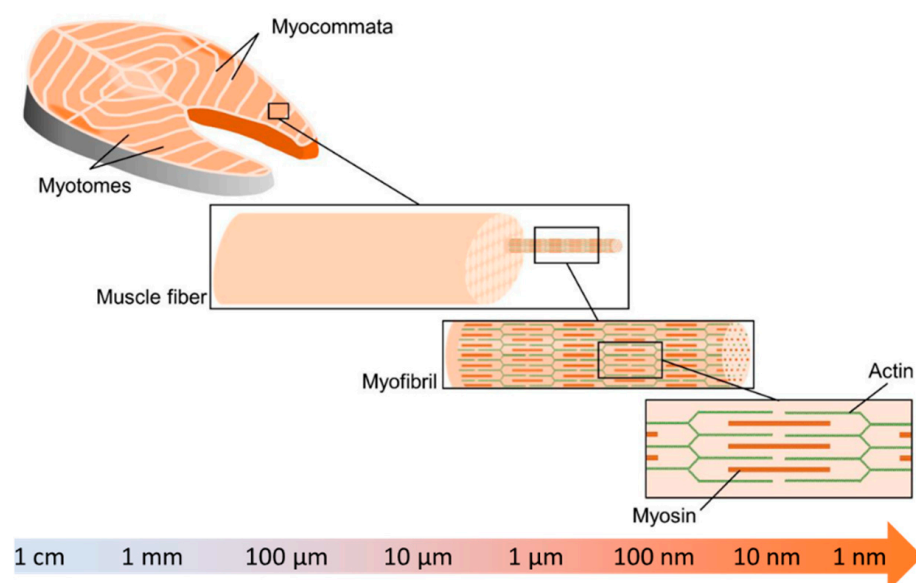


Figure 2. A schematic diagram indicating the hierarchical structures of fish muscle structure (Adapted from Kazir and others with permission) [29].

3.1. Fish Muscle Structure

Striated muscle and smooth muscle are the two main types of muscle in fish. Striated muscle, the major fraction of fish muscle, is characterized by transverse stripe and consists of white, red, and intermediate pink muscles with more than 90% of white muscle [30,31]. White muscle is characterized by its white to off-white color in most fish species [16], and it is the major constituent of the myotomal musculature in fish fillets with fiber diameter in the range of 50 to 100 μm (Figure 2) [31,32]. The red color in certain marine fish species, such as salmon and trout, is due to red carotenoids, rather than myoglobin [33]. From a functional point of view, since the white muscle works as sprinting muscle for prey to capture and escape from predators and is active at high cruising speed, it is also known as fast muscle [31,34]. On the other hand, among these three muscle types, red muscle presents the smallest fiber diameter in the range of 25 to 45 μm , but higher levels of lipids, haemoglobin, glycogen, and vitamins [33]. This protein is in the superficial area along the skin [35], and its major function is to provide slow and continuous movement [33]. Pink muscle, in pink color, is also called the intermediate muscle because of the intermediate region between red and white muscle [35,36]. Pink muscle fibers are recruited at an intermediate speed between white and red muscle fibers [34]. Although there is a functional separation between red and white muscle fibers as the slow and fast fibers, this separation of roles is not absolute.

3.2. Fish Muscle Alignment

Fish muscle is generally similar to terrestrial animal muscle in their composition and function [37]. The most distinguishable difference in striated muscle structure between fish and common livestock is their separation of different types of muscle fiber [31]. The edible part of the fish fillet could be further divided into myotomes (muscle fiber) arranged alternately with myocommata in a W-shaped pattern or connective tissue [35,38]. Another distinctive difference between fish muscles against terrestrial animals is the anatomical separation of fish muscles macroscopically into three groups: namely white muscle, red muscle, and intermediate pink muscle [35]. Overall, finfish have a lower collagen content than terrestrial animals [16]. The reason for the lower collagen content in finfish is that fish live in an environment that does not require as much support as terrestrial animals do [38]. Furthermore, the solubility of fish collagen is considerably higher than that of terrestrial mammals [39]. Lower collagen content in fish could potentially contribute to a softer fish fillet texture than a terrestrial animal fillet. Different from terrestrial animals, in which their muscle fibers are embedded in more complex hierarchical layers of connective tissue, fish lack the tendinous system that can connect muscle bundles to the skeleton [40,41]. Myocommata in fish can work similarly to the epimysia in terrestrial animals [35]. The absence of these collagenous fibers and tendons in fish makes them easier to be digested and absorbed [17]. Fibers in fish muscle have a diameter ranging from 10 to 100 μm and are shorter (the scale of millimeters) than those in terrestrial animals (usually a few centimeters) [35]. The muscle fibers are comprised of 1000 to 2000 myofibrils packed together into bundles, and each has a diameter of up to 5 μm . Myotomes in fish fillets consist of muscle fibers that run parallel to the longitudinal direction of the fish [16].

4. Processing Techniques to Produce Fish Analogue

Considering the complicated structures of fish protein, it is noteworthy that the preparation of fish fillet analogues requires more elaborate techniques to resemble the texture and appearance of fish meat when compared to the comminuted meat analogues production. Generally, two main strategies, namely the bottom-up strategy and top-down strategy, have been used to process plant-based meat analogues [42]. Bottom-up strategy assembles individual elements into a larger structure, even resembling the meaty hierarchical structure down to the nanoscale. However, the problems associated with this strategy include the cost of mass production and processing reliability [42]. On the other hand, a top-down approach imitates the structure of meat only on a much larger length

scale, and could create anisotropic and fibrous products. It has a better scalability chance for economic application [42]. Nonetheless, the question associated with top-down strategy includes whether or not it could sufficiently mimic the actual meat products [42].

To date, very little success has been had in producing fish analogues from plant-based proteins, but there are a handful of cases where novel processing techniques were developed to modulate plant proteins for other applications, such as nanofibers, edible films, meat analogues, and gels (Table 3). Those applications revealed the underlying mechanisms of plant protein behaviors under different processing conditions as well as their interactions with other compounds, which could be used to guide the process design of plant protein-based fish analogues. Each promising technique will then be extensively discussed in terms of its potential application for fish analogue production. Moreover, current successful commercial plant-based meat products focus on comminuted meat products such as sausage and burgers, where a list of functional ingredients was used. According to Table 4, the functionalities of these ingredients are binding agents and stabilizers, which aim to modulate the texture and mouthfeel of the plant-based products. More recently, DSM[®] developed and commercialized a fish flavor [43], which enables manufacturers to formulate authentic, tasty, and enticing vegan seafood products.

Table 3. A summary of processing techniques to obtain different plant protein-based products.

Processing Techniques	Raw Material	Products	References
Electrospinning	Soy protein isolate and alginate	Nanofibers	[44]
Wet spinning	Soy protein isolate	Edible films	[45]
Extrusion	Hemp and soy protein	Meat analogue	[46]
Extrusion	Soy and algae	Meat analogue	[47]
3D printing	Soy protein isolate and xanthan gum	Gels	[48]
Extrusion	Pea protein and oat fiber	Fibrous Meat analogue	[49]

Table 4. Common ingredients used in plant-based products and functionalities.

Ingredients	Functionality	Example of Food	Reference
Polysaccharide (Carrageenan; Methylcellulose)	Texture enhancement; thickening agent	Meat analogues	[50]
Oleosomes	Emulsification/Stabilization	Meat analogues	[51]
Plant fat (Coconut oil; Canola oil; Sunflower oil)	Texture (juiciness) enhancement	Plant-based burger	[50]
Leghemoglobin	Meat flavor	Plant-based meat	[52]
Maxavor [®] Fish YE	Fish flavor	Plant-based seafood	[43]

4.1. Electrospinning

Electrospinning (Figure 3a) is a robust, cost-effective, and rapid technique for producing structured fibrous food with interconnected pores in sub-micron range [53]. Some unique features of electrospun nanofibers include high surface-to-volume ratio, tunable porosity, flexibility in conforming to different sizes and shapes, fiber morphology, and mechanical strength [53]. Recently, the application of electrospinning has been extended to processing plant-based proteins as meat analogues. Plant proteins, such as soy proteins and pea proteins, contain a mixture of various protein fractions with molecular weights ranging from 200 to 600 kDa [54]. In the past, collagen and gelatin have been widely studied for electrospinning due to their naturally fibrous structure [54]. Globular proteins, such as soy protein, have to go through an unfolding and denaturation process prior to electrospinning [54]. Recent work reported that a combined treatment of alkaline and

thermal at a pH above 4.5 could help to unfold and solubilize soy proteins via exposing hydrophobic and sulfhydryl groups [54].

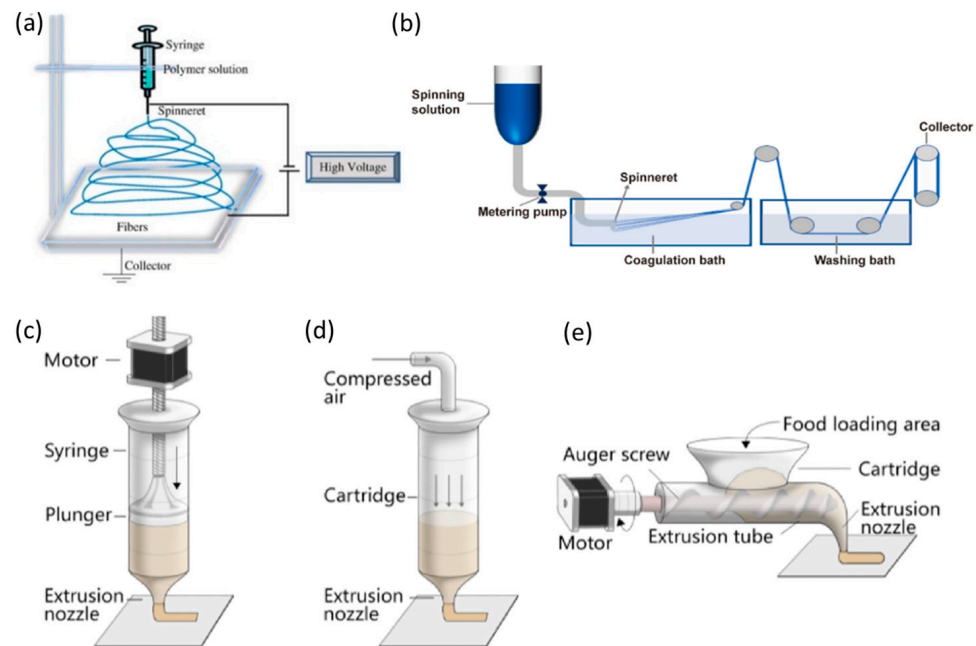


Figure 3. (a) Standard vertical setups of electrospinning process setup reprinted from [53] with permission. (b) Schematic description of a wet-spinning process for plant proteins, reprinted from [55]. (c) Syringe-based type extrusion, (d) air-pressure-driven extrusion, (e) screw-based type extrusion. (c–e) reprinted from Sun and others with permission [56].

In fish analogue processing, it is critical to revitalizing the unique microstructure to ensure the proper texture. Therefore, precise alignment of fibrous proteins is necessary through electrospinning to achieve the highly ordered W-shape patterns to mimic the alignment of myotomes. An approach has been reported that can simultaneously combine electrospinning and electro-spraying to process two heterogeneous materials [57], demonstrating the potential of producing fish analogues through a precise bottom-up assembly of hierarchical microstructure. However, more research needs to be performed to improve the throughput and lower the production cost. In addition, most of the current solvents to unfold and solubilize plant proteins are toxic, such as hexafluoroisopropanol (HFIP) and trifluoroethanol (TFE) [54], more food-grade alternative solvents need to be explored.

4.2. Wet Spinning

Similar to electrospinning, wet spinning requires pumping polymer solution through a spinneret that is usually immersed in an acid bath, where the spun filaments can solidify, and then the solidified fibers can be collected and form a continuous tow and rope [58]. Wet spinning (Figure 3b) is considered a mild process because it operates at lower temperatures, which could be more feasible for processing food products.

Due to its capability of producing a variety of fiber cross-sectional structures, wet spinning also presents great potential in structuring plant proteins. A pioneering study used wet spinning to process soy protein to produce edible films, and the produced fibrous soy protein film exhibited strong tensile strength at 3.9 MPa and 55 MPa of Young's modulus [45]. Although the number could vary significantly by fish species, the Young's modulus of the fish fillet is much smaller than the edible film and meat. According to recent work, the magnitude of Young's modulus in fish is around 10 KPa or 0.01 MPa [59], compared to 55 MPa in protein film and 0.1 MPa in beef [60]. Additionally, fish fillet has a 6 KPa to 10 KPa of loss modulus, indicating a mild weak network structure.

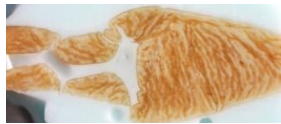



Boyer patented the wet spinning of proteins for the application of meat analogues in 1954 [42]. They extruded the solubilized soy protein through a spinneret and obtained stretched protein filaments with a thickness in the order of 20 μm [61]. The structure of a wet-spun protein can be modulated by controlling the solidification process. Depending on the manipulation of the continuous phase and dispersed phase, capillary-filled gels and fiber-filled gels can be obtained [62]. The modulation of protein structure in wet-spinning is on a larger scale, where the secondary structure and tertiary structure did not shift significantly after processing [59]. The restricted capability of controlling the secondary and tertiary structure of proteins may limit the application of wet spinning in producing fish analogues with desirable textures.

4.3. 3D-Printing

Three-dimensional printing (3D printing) can be printed in micron size and has been gaining increasing attention in the food industry as a novel processing technique to produce novel food, such as recombined meat products, in the last few decades [63]. In addition to animal proteins, a wide range of plant-based materials have also been extensively studied for 3D printing, such as soy protein, pea protein, and wheat protein [52]. Many successes were achieved using soy proteins to produce a variety of meat analogues [64,65]. Although there has been a lot of work completed, challenges remain for 3D printing using plant-based proteins, especially regarding the structural reconstructive to obtain proper texture and to deliver the fine resolution of printed constructs with an appreciable mouthfeel. It was found that plant proteins without additives or pretreatments lack the capability needed to form a proper 3D structure [66].

A few strategies have been proposed to finely tune the 3D structure and viscoelastic properties of 3D-printed plant-based foods, which could be summarized in three categories: (1) process control, (2) co-printing with other biopolymers, and (3) use of enzymes. Process control is the most facile approach to modulate the structural and rheological properties of plant proteins during 3D printing. For example, a heating–cooling procedure has been found to improve the printing quality and accuracy of soy-based products [64]. In regard to co-printing, surface-active biopolymers (e.g., OSA-modified starch) have been found to significantly improve the shear-thinning behavior, and an increase in biosurfactants concentration led to an increase in viscosity recovery, yield stress, and elastic modulus [65]. It was also reported that monodispersed biosurfactants with a greater radius of gyration provide stronger pseudoplasticity [65]. Other than surface-active polymers, xanthan gum, gelatin, sodium alginate, and sodium chloride were found to strengthen the 3D printing structure for soy protein [48], yet more mechanistic insights are still needed. Enzymatic treatments could also be useful in modulating plant-based proteins during 3D printing. Transglutaminase (TGase), a very popular cold-set binder, could be used in restructured food and in plant-based products (e.g., pea, soy, wheat) [67], to help bind different meat analogues cohesively [68]. To date, very few approaches have explored the possibility of using 3D printing to produce fish analogues from plant-based proteins. It is expected that a combination of those above-mentioned strategies, including precise processing, the addition of synergistic biopolymers, and the application of enzymatic treatments, will enable fine control of the printed protein microstructure to achieve the unique mouthfeel of fish products. Examples of 3D-printed plant protein products can be found in Table 5.

Table 5. Plant-based meat analogues with different processing techniques.

Techniques	Plant Protein Sources	Processing Parameters	Images	Ref.
High moisture extrusion	Soy protein isolate	Extrusion temperature = 95 °C, Screw speed = 600 rpm, Moisture content = 57%		[46]
3D printing	Pea protein isolate	Nozzle diameter = 1.54 mm, Extrusion speed = 15 mm/s		[69]
High moisture extrusion	Soy protein isolate	Extrusion temperature = 124 °C, Screw speed = 250 rpm, Water content = 50%		[70]
3D printing	Textured soybean protein	Nozzle diameter = 0.8 mm, Extrusion speed = 20 mm/s		[71]

4.4. Extrusion

High moisture extrusion (>40%) is frequently used for producing soy-based meat analogs [47], as it has many advantages, such as higher energy efficiency and less production expansion [72]. However, extrusion is an extremely complex processing technique that involves a variety of chemical and physical evolutions simultaneously [73]. Therefore, temperature control during the extrusion processing is the key to achieving desirable protein structure and texture. For example, in the production of soy protein-based meat analogs, the number of temperature zones can vary from four to nine in order to precisely control the plant protein structure [46,47,74]. The highest cooking temperature zone, which has the most profound impact on protein texturization, is usually set in the middle or rear-end of the barrel [75,76]. More importantly, recent work found that a high processing temperature could produce a V-shape structure, which attributes to the laminar flow in the die section [46] and can potentially mimic the mouthfeel of fish muscle. In addition to temperature control, protein and moisture content are also critical in determining the product properties. Using soy protein as an example, high moisture content (~77%) leads to a juicier and softer meat analogue, which is perceived as less fibrous but mushy mouthfeel in sensory evaluation [47]. On the other hand, higher protein content in plant materials allows the formation of more chemical bonds and contributes to the formation of a more chewy texture during extrusion [77]. Modulating texture profile by extrusion parameters to mimic fish fillet is yet to be explored, but current findings from meat analogue may suggest an extrusion process with high temperature, low protein concentration, and high moisture content could be preferable.

Other than process control, a list of functional ingredients could be incorporated to further improve the product quality, including texture profile, flavor profile, and color development [78]. Leghemoglobin has been successfully applied by Impossible Foods™ to provide a meaty flavor and a red-to-brown color change upon cooking [52,78]. Since

fish fillet has a distinctive color and flavor when compared to meat products, alternative additives will be needed to imitate fish products. It has been found that norbixin could potentially help to mimic the yellowish color in salmon to give a red-yellow color [79]. Compounds such as furans and thiophenes can provide a strong meaty aroma at low threshold values [80]. The addition of oil during the processing can contribute to juicier, tenderer meat analogs, and helps flavor release [81]. Common practice is to combine solid oil (e.g., coconut oil, palm oil) with liquid oil (e.g., sunflower oil, canola oil) to improve mouthfeel and juiciness during meat analogs production [50]. Examples of plant-based meat analogues from high moisture extrusion can be found in the Table 5.

5. Conclusions

The concept of developing fish and seafood analogues based on plant protein sources has been proposed recently [29]. However, there are still very limited successful applications of plant-based seafood analogues. This study has explored the nutritional properties of plant-based materials and has compared their nutritional properties, noticeably their protein quality with fish as it is nowadays being regarded as a novel source for plants compared to terrestrial meat. A combination of plant proteins from different sources makes it possible to achieve a very high PDCAAS comparable to fish protein. The difference in fish muscle and terrestrial animal muscle structure, both macroscopically and microscopically, has been emphasized. The main difference in fish muscles is their unique W-shaped muscle structure and the separation of myotome and myocommata. The fact that fish are not frequently consumed in the forms of value-added products such as ham and sausage renders a big challenge in producing fish analogues. However, various processing techniques have been proposed. Some techniques show potential in producing fish analogues that can emulate the unique W-shaped muscle structure, such as electrospinning and 3D printing.

Challenges and hurdles: Although there have been successful applications of plant-based beef burgers and sausage, most applications are mainly minced meat, lacking the characteristic appearance of whole-cut meat fillet. This could be due to the processing techniques for present plant-based meat analogues, that is, extrusion. This technology is applied generally to produce a product that only gives a consistent look. Despite the absence of the characteristic appearance of marine fish fillets, mimicking the texture of fish fillets is another factor that hinders the mass production of plant-based protein. Moreover, the connective tissue in cooked fish fillets could be destabilized, contributing to breaking the W-shaped structure upon mastication. Imitation of this behavior is yet another critical challenge. There have been some emerging processing technologies recently, such as wet spinning and electrospinning, which show the potential of producing fish analogue with their characteristic appearance and texture. However, these technologies are mainly used for scientific research, and the cost of these technologies is too high for mass production. Although plant-proteins are widely recognized as a sustainable alternative to animal proteins, their negative environmental impact during production also needs to be properly handled. For example, typical soybean has a protein content of 30 to 40% [8], and a high amount of waste stream could be produced during the soybean protein extraction procedure [82], yet more efficient soybean protein extraction methods are still underway.

Future perspectives: Traditional processing techniques to produce meat analogues limit the development of meat analogues with a more refined texture. In this light, more novel processing techniques that focus on producing analogues more microscopically have been developed. Comparing all the current processing techniques, extrusion is the predominately used technique in the current industry, while 3D-printing and electrospinning have shown the prominent potential of mimicking fish muscle structure as bottom-up approaches. However, their applicability for producing fish analogues needs further investigation. Furthermore, whether these techniques could work in combination also needs to be proved. Although it is possible to produce a fish analogue with the typical fish

fillet appearance with these novel processing methods, their behavior upon cooking is another critical problem affecting their texture when consumed, and more studies need to be conducted on this subject. Finally, more studies are required to study the emulation of fish innate flavor.

Author Contributions: Conceptualization, C.Z. and Y.F.; methodology, C.Z. and Y.F.; writing—original draft preparation, C.Z., Y.X. and Y.F.; writing—review and editing, C.Z., Y.X. and Y.F.; visualization, C.Z.; supervision, Y.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data are available from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. The World Bank Population. Available online: <https://data.worldbank.org/indicator/SP.POP.TOTL> (accessed on 20 April 2022).
2. Ritchie, H.; Roser, M. Fish and Overfishing. Available online: <https://ourworldindata.org/fish-and-overfishing#how-much-fish-do-people-eat> (accessed on 20 April 2022).
3. World Wild Life Overfishing. Available online: <https://www.worldwildlife.org/threats/overfishing> (accessed on 20 April 2022).
4. FAO. The State of World Fisheries and Aquaculture 2020. Available online: <https://www.fao.org/state-of-fisheries-aquaculture> (accessed on 20 April 2022).
5. Naylor, R.L.; Goldburg, R.J.; Primavera, J.H.; Kautsky, N.; Beveridge, M.C.M.; Clay, J.; Folke, C.; Lubchenco, J.; Mooney, H.; Troell, M. Effect of Aquaculture on World Fish Supplies. *Nature* **2000**, *405*, 1017–1024. [CrossRef] [PubMed]
6. Cole, D.W.; Cole, R.; Gaydos, S.J.; Gray, J.; Hyland, G.; Jacques, M.L.; Powell-Dunford, N.; Sawhney, C.; Au, W.W. Aquaculture: Environmental, Toxicological, and Health Issues. *Int. J. Hyg. Environ. Health* **2009**, *212*, 369–377. [CrossRef] [PubMed]
7. Ahmad, A.; Sheikh Abdullah, S.R.; Hasan, H.A.; Othman, A.R.; Ismail, N. Izzati Aquaculture Industry: Supply and Demand, Best Practices, Effluent and Its Current Issues and Treatment Technology. *J. Environ. Manag.* **2021**, *287*, 112271. [CrossRef] [PubMed]
8. Vollmann, J.; Fritz, C.N.; Wagentristsl, H.; Ruckenbauer, P. Environmental and Genetic Variation of Soybean Seed Protein Content under Central European Growing Conditions. *J. Sci. Food Agric.* **2000**, *80*, 1300–1306. [CrossRef]
9. Serkissian, Madeleine Seven of the Biggest Problems Facing Fish in Our Oceans. Available online: <https://marine-conservation.org/on-the-tide/seven-of-the-biggest-problems-facing-fish-in-our-oceans> (accessed on 16 January 2023).
10. Heal, G.; Schlenker, W. Sustainable Fisheries. *Nature* **2008**, *455*, 1044–1045. [CrossRef]
11. Wanjala, Caiaphas Top 10 Most Consumed Fish in the World in 2021. Available online: <https://www.tuko.co.ke/406008-top-10-consumed-fish-world-2021-photos.html> (accessed on 31 December 2022).
12. Ghaedian, R.; Decker, E.A.; McClements, D.J. Use of Ultrasound to Determine Cod Fillet Composition. *J. Food Sci.* **1997**, *62*, 500–504. [CrossRef]
13. Isaksson, T.; Tøgersen, G.; Iversen, A.; Hildrum, K.I. Non-destructive Determination of Fat, Moisture and Protein in Salmon Fillets by Use of Near-infrared Diffuse Spectroscopy. *J. Sci. Food Agric.* **1995**, *69*, 95–100. [CrossRef]
14. Khodabux, K.; L’Omelette, M.S.S.; Jhaumeer-Laulloo, S.; Ramasami, P.; Rondeau, P. Chemical and Near-Infrared Determination of Moisture, Fat and Protein in Tuna Fishes. *Food Chem.* **2007**, *102*, 669–675. [CrossRef]
15. Petricorena, Z.C. Chemical composition of fish and fishery products. In *Handbook of Food Chemistry*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 403–435. ISBN 9783642366055.
16. Venugopal, V.; Shahidi, F. Structure and Composition of Fish Muscle. *Food Rev. Int.* **1996**, *12*, 175–197. [CrossRef]
17. Tahergorabi, R.; Hosseini, S.V.; Jaczynski, J. *Seafood Proteins*; Woodhead Publishing Limited: Sawston, UK, 2011.
18. Schaafsma, G. The Protein Digestibility-Corrected Amino Acid Score (PDCAAS)—A Concept for Describing Protein Quality in Foods and Food Ingredients: A Critical Review. *J. AOAC Int.* **2005**, *88*, 988–994. [CrossRef]
19. El, S.N.; Kavas, A. Determination of Protein Quality of Rainbow Trout (*Salmo Irideus*) by in Vitro Protein Digestibility-Corrected Amino Acid Score (PDCAAS). *Food Chem.* **1996**, *55*, 221–223. [CrossRef]
20. Usydu, Z.; Szlinder-Richert, J.; Adamczyk, M. Protein Quality and Amino Acid Profiles of Fish Products Available in Poland. *Food Chem.* **2009**, *112*, 139–145. [CrossRef]
21. Pyz-Lukasik, R.; Paszkiewicz, W. Species Variations in the Proximate Composition, Amino Acid Profile, and Protein Quality of the Muscle Tissue of Grass Carp, Bighead Carp, Siberian Sturgeon, and Wels Catfish. *J. Food Qual.* **2018**, *2018*, 2625401. [CrossRef]
22. Ertl, P.; Knaus, W.; Zollitsch, W. An Approach to Including Protein Quality When Assessing the Net Contribution of Livestock to Human Food Supply. *Animal* **2016**, *10*, 1883–1889. [CrossRef] [PubMed]
23. Hughes, G.J.; Ryan, D.J.; Mukherjea, R.; Schasteen, C.S. Protein Digestibility-Corrected Amino Acid Scores (PDCAAS) for Soy Protein Isolates and Concentrate: Criteria for Evaluation. *J. Agric. Food Chem.* **2011**, *59*, 12707–12712. [CrossRef]

24. Mariotti, F. *Plant Protein, Animal Protein, and Protein Quality*; Elsevier: Amsterdam, The Netherlands, 2017; ISBN 9780128039694.
25. Berry, T.H.; Becker, D.E.; Rasmussen, O.G.; Jensen, A.H.; Norton, H.W. The Limiting Amino Acids in Soybean Protein. *J. Anim. Sci.* **1962**, *21*, 558–561. [\[CrossRef\]](#)
26. Nikmaram, N.; Leong, S.Y.; Koubaa, M.; Zhu, Z.; Barba, F.J.; Greiner, R.; Oey, I.; Roohinejad, S. Effect of Extrusion on the Anti-Nutritional Factors of Food Products: An Overview. *Food Control* **2017**, *79*, 62–73. [\[CrossRef\]](#)
27. Nigam, P.S.; Singh, A. *Single Cell Protein: Mycelial Fungi*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2014; Volume 3, ISBN 9780123847331.
28. Sarwar, G.; Peace, R.W.; Botting, H.G.; Brulé, D. Digestibility of Protein and Amino Acids in Selected Foods as Determined by a Rat Balance Method. *Plant Foods Hum. Nutr.* **1989**, *39*, 23–32. [\[CrossRef\]](#)
29. Kazir, M.; Livney, Y.D. Plant-Based Seafood Analogs. *Molecules* **2021**, *26*, 1559. [\[CrossRef\]](#)
30. Torres, J.A.; Rodrigo-García, J.; Jaczynski, J.; Chen, Y.C. Recovery of By-Products from Seafood Processing Streams. In *Maximising Value Marine By-Products*; Woodhead Publishing Limited: Sawston, UK, 2006; pp. 65–90. [\[CrossRef\]](#)
31. Kiessling, A.; Ruohonen, K.; Bjørnevik, M. Muscle Fibre Growth and Quality in Fish. *Arch. Tierz. Dummerstorf* **2016**, *49*, 137–146.
32. Coughlin, D.J.; Rome, L.C. The Roles of Pink and Red Muscle in Powering Steady Swimming in Scup, *Stenotomus Chrysops*. *Am. Zool.* **1996**, *36*, 666–677. [\[CrossRef\]](#)
33. Nowsad, A. Structure of Fish Muscles and Composition of Fish. In *Participatory Training of Trainers- A New Approach Applied in Fish Processing*; Bangladesh Fisheries Research Forum: Dhaka, Bangladesh, 2007; p. 329.
34. Johnston, I.A.; Davison, W.; Goldspink, G. Energy Metabolism of Carp Swimming Muscles. *J. Comp. Physiol. B* **1977**, *114*, 203–216. [\[CrossRef\]](#)
35. Listrat, A.; Lebret, B.; Louveau, I.; Astruc, T.; Bonnet, M.; Lefaucheur, L.; Bugeon, J. How Muscle Structure and Composition Determine Meat Quality. *Prod. Anim.* **2015**, *28*, 125–136.
36. Mascarello, E.; Romanello, M.G.; Scapolo, P.A. Histochemical and Immunohistochemical Profile of Pink Muscle Fibres in Some Teleosts. *Histochemistry* **1986**, *84*, 251–255. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Tahergorabi, R.; Jaczynski, J. Physicochemical Changes in Surimi with Salt Substitute. *Food Chem.* **2012**, *132*, 1281–1286. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Hultin, H.O. Postmortem Biochemistry of Meat and Fish. *J. Chem. Educ.* **1984**, *61*, 289–298. [\[CrossRef\]](#)
39. Sato, K.; Yoshinaka, R.; Sato, M.; Shimizu, Y. Collagen Content in the Muscle of Fishes in Association with Their Swimming Movement and Meat Texture. *Nippon SUISAN GAKKAISHI* **1986**, *52*, 1595–1600. [\[CrossRef\]](#)
40. FAO Quality and Quality Changes in Fresh Fish. Available online: <https://www.fao.org/3/V7180E/V7180E04.htm> (accessed on 20 April 2022).
41. LAMPILA, L.E. Comparative Microstructure of Red Meat, Poultry and Fish Muscle. *J. Muscle Foods* **1990**, *1*, 247–267. [\[CrossRef\]](#)
42. Dekkers, B.L.; Boom, R.M.; van der Goot, A.J. Structuring Processes for Meat Analogues. *Trends Food Sci. Technol.* **2018**, *81*, 25–36. [\[CrossRef\]](#)
43. Austin, Mark Vegan Fish Flavors That Deliver More, Naturally. Available online: https://www.dsm.com/food-beverage/en_US/insights/insights/savory/plant-based-seafood.html (accessed on 31 December 2022).
44. Wongkanya, R.; Chuysinuan, P.; Pengsuk, C.; Techasakul, S.; Lirdprapamongkol, K.; Svasti, J.; Nooeaid, P. Electrospinning of Alginate/Soy Protein Isolated Nanofibers and Their Release Characteristics for Biomedical Applications. *J. Sci. Adv. Mater. Devices* **2017**, *2*, 309–316. [\[CrossRef\]](#)
45. Rampon, V.; Robert, P.; Nicolas, N.; Dufour, E. Protein Structure and Network Orientation in Edible Films Prepared by Spinning Process. *J. Food Sci.* **1999**, *64*, 313–316. [\[CrossRef\]](#)
46. Wittek, P.; Ellwanger, F.; Karbstein, H.P.; Emin, M.A. Morphology Development and Flow Characteristics during High Moisture Extrusion of a Plant-Based Meat Analogue. *Foods* **2021**, *10*, 1753. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Grahl, S.; Palanisamy, M.; Strack, M.; Meier-Dinkel, L.; Toepfl, S.; Mörlein, D. Towards More Sustainable Meat Alternatives: How Technical Parameters Affect the Sensory Properties of Extrusion Products Derived from Soy and Algae. *J. Clean. Prod.* **2018**, *198*, 962–971. [\[CrossRef\]](#)
48. Phuhongsung, P.; Zhang, M.; Devahastin, S. Investigation on 3D Printing Ability of Soybean Protein Isolate Gels and Correlations with Their Rheological and Textural Properties via LF-NMR Spectroscopic Characteristics. *LWT* **2020**, *122*, 109019. [\[CrossRef\]](#)
49. Ramos Diaz, J.M.; Kantanen, K.; Edelmann, J.M.; Suhonen, H.; Sontag-Strohm, T.; Jouppila, K.; Piironen, V. Fibrous Meat Analogues Containing Oat Fiber Concentrate and Pea Protein Isolate: Mechanical and Physicochemical Characterization. *Innov. Food Sci. Emerg. Technol.* **2022**, *77*, 102954. [\[CrossRef\]](#)
50. Avebe, Kyriakopoulou, K.; Keppler, J.K.; Van Der Goot, A.J. Vegan Meat Analogues. *Foods* **2020**, *10*, 9147.
51. Karefyllakis, D.; van der Goot, A.J.; Nikiforidis, C.V. Multicomponent Emulsifiers from Sunflower Seeds. *Curr. Opin. Food Sci.* **2019**, *29*, 35–41. [\[CrossRef\]](#)
52. Ramachandraiah, K. Potential Development of Sustainable 3d-Printed Meat Analogues: A Review. *Sustainability* **2021**, *13*, 938. [\[CrossRef\]](#)

53. Bhardwaj, N.; Kundu, S.C. Electrospinning: A Fascinating Fiber Fabrication Technique. *Biotechnol. Adv.* **2010**, *28*, 325–347. [\[CrossRef\]](#)
54. Vega-Lugo, A.-C.; Lim, L.-T. Electrospinning of Soy Protein Isolate Nanofibers. *J. Biobased Mater. Bioenergy* **2008**, *2*, 223–230. [\[CrossRef\]](#)
55. Cui, B.; Liang, H.; Li, J.; Zhou, B.; Chen, W.; Liu, J.; Li, B. Development and Characterization of Edible Plant-Based Fibers Using a Wet-Spinning Technique. *Food Hydrocoll.* **2022**, *133*, 107965. [\[CrossRef\]](#)
56. Sun, J.; Zhou, W.; Yan, L.; Huang, D.; Lin, L.-y. Extrusion-Based Food Printing for Digitalized Food Design and Nutrition Control. *J. Food Eng.* **2018**, *220*, 1–11. [\[CrossRef\]](#)
57. Lavielle, N.; Hébraud, A.; Schlatter, G.; Thöny-Meyer, L.; Rossi, R.M.; Popa, A.M. Simultaneous Electrospinning and Electrospraying: A Straightforward Approach for Fabricating Hierarchically Structured Composite Membranes. *ACS Appl. Mater. Interfaces* **2013**, *5*, 10090–10097. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Ozipek, B.; Karakas, H. Wet Spinning of Synthetic Polymer Fibers. In *Advances in Filament Yarn Spinning of Textiles and Polymers*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 174–186. ISBN 9780857094995.
59. Feneuil, B.; Strøm Lillebø, E.; Honstad, C.L.; Jensen, A.; Carlson, A. Elastic Modulus Measurements of Cooked Lutefisk. *Phys. Fluids* **2022**, *34*, 047122. [\[CrossRef\]](#)
60. James, B.; Yang, S.W. Testing Meat Tenderness Using an in Situ Straining Stage with Variable Pressure Scanning Electron Microscopy. *Procedia Food Sci.* **2011**, *1*, 258–266. [\[CrossRef\]](#)
61. Boyer, R.A. High Protein Food Product and Process for Its Preparation. US Patent 2,682,466, 1954.
62. TOLSTOGUZOV, V.B. CREATION OF FIBROUS STRUCTURES BY SPINNERETLESS SPINNING. In *Food Structure*; Elsevier: Amsterdam, The Netherlands, 1988; pp. 181–196.
63. Dick, A.; Bhandari, B.; Prakash, S. 3D Printing of Meat. *Meat Sci.* **2019**, *153*, 35–44. [\[CrossRef\]](#)
64. Chen, J.; Mu, T.; Goffin, D.; Blecker, C.; Richard, G.; Richel, A.; Haubruge, E. Application of Soy Protein Isolate and Hydrocolloids Based Mixtures as Promising Food Material in 3D Food Printing. *J. Food Eng.* **2019**, *261*, 76–86. [\[CrossRef\]](#)
65. Shahbazi, M.; Jäger, H.; Ettelaie, R.; Chen, J. Construction of 3D Printed Reduced-Fat Meat Analogue by Emulsion Gels. Part I: Flow Behavior, Thixotropic Feature, and Network Structure of Soy Protein-Based Inks. *Food Hydrocoll.* **2021**, *120*, 106967. [\[CrossRef\]](#)
66. Godoi, F.C.; Prakash, S.; Bhandari, B.R. 3d Printing Technologies Applied for Food Design: Status and Prospects. *J. Food Eng.* **2016**, *179*, 44–54. [\[CrossRef\]](#)
67. Shand, P.J.; Ya, H.; Pietrasik, Z.; Wanasundara, P.K.J.P.D. Transglutaminase Treatment of Pea Proteins: Effect on Physicochemical and Rheological Properties of Heat-Induced Protein Gels. *Food Chem.* **2008**, *107*, 692–699. [\[CrossRef\]](#)
68. Dong, X.; Pan, Y.; Zhao, W.; Huang, Y.; Qu, W.; Pan, J.; Qi, H.; Prakash, S. Impact of Microbial Transglutaminase on 3D Printing Quality of *Scomberomorus Nipponius* Surimi. *LWT* **2020**, *124*, 109123. [\[CrossRef\]](#)
69. Wang, T.; Kaur, L.; Furuhashi, Y.; Aoyama, H.; Singh, J. 3D Printing of Textured Soft Hybrid Meat Analogues. *Foods* **2022**, *11*, 478. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Wittek, P.; Zeiler, N.; Karbstein, H.P.; Emin, M.A. High Moisture Extrusion of Soy Protein: Investigations on the Formation of Anisotropic Product Structure. *Foods* **2021**, *10*, 102. [\[CrossRef\]](#) [\[PubMed\]](#)
71. Chen, Y.; Zhang, M.; Bhandari, B. 3D Printing of Steak-Like Foods Based on Textured Soybean Protein. *Foods* **2021**, *10*, 2011. [\[CrossRef\]](#) [\[PubMed\]](#)
72. Cheftel, J.C.; Kitagawa, M.; Queguiner, C. New Protein Texturization Processes by Extrusion Cooking at High Moisture Levels. *Food Rev. Int.* **1992**, *8*, 235–275. [\[CrossRef\]](#)
73. Feng, Y.; Lee, Y. Effect of Specific Mechanical Energy on In-Vitro Digestion and Physical Properties of Extruded Rice-Based Snacks. *Food Nutr. Sci.* **2014**, *05*, 1818–1827. [\[CrossRef\]](#)
74. Zahari, I.; Ferawati, F.; Helstad, A.; Ahlström, C.; Östbring, K.; Rayner, M.; Purhagen, J.K. Development of High-Moisture Meat Analogues with Hemp and Soy Protein Using Extrusion Cooking. *Foods* **2020**, *9*, 772. [\[CrossRef\]](#)
75. Lin, S.; Huff, H.E.; Hsieh, F. Extrusion Process Parameters, Sensory Characteristics, and Structural Properties of a High Moisture Soy Protein Meat Analog. *J. Food Sci.* **2002**, *67*, 1066–1072. [\[CrossRef\]](#)
76. Chen, F.L.; Wei, Y.M.; Zhang, B. Chemical Cross-Linking and Molecular Aggregation of Soybean Protein during Extrusion Cooking at Low and High Moisture Content. *LWT* **2011**, *44*, 957–962. [\[CrossRef\]](#)
77. Samard, S.; Ryu, G.H. Physicochemical and Functional Characteristics of Plant Protein-Based Meat Analogs. *J. Food Process. Preserv.* **2019**, *43*, e14123. [\[CrossRef\]](#)
78. McClements, D.J.; Grossmann, L. The Science of Plant-Based Foods: Constructing next-Generation Meat, Fish, Milk, and Egg Analogs. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 4049–4100. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Bolognesi, V.J.; Garcia, C.E.R. Annatto Carotenoids as Additives Replacers in Meat Products. In *Alternative and Replacement Foods*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 355–384.
80. Mottram, D.S.; Madruga, M.S.; Whitfield, F.B. Some Novel Meatlike Aroma Compounds from the Reactions of Alkanediones with Hydrogen Sulfide and Furanthiols. *J. Agric. Food Chem.* **1995**, *43*, 189–193. [\[CrossRef\]](#)

81. Beniwal, A.S.; Singh, J.; Kaur, L.; Hardacre, A.; Singh, H. Meat Analogs: Protein Restructuring during Thermomechanical Processing. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 1221–1249. [[CrossRef](#)] [[PubMed](#)]
82. Preece, K.E.; Hooshyar, N.; Zuidam, N.J. Whole Soybean Protein Extraction Processes: A Review. *Innov. Food Sci. Emerg. Technol.* **2017**, *43*, 163–172. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.