sustainability

MDPI

Article

Use of Organic Wastes and Industrial By-Products to Produce Filamentous Fungi with Potential as Aqua-Feed Ingredients

Sajjad Karimi [1,2], Nasrollah Mahboobi Soofiani [1], Amir Mahboubi [2,3,*] and Mohammad J. Taherzadeh [2]

1. Fisheries Division, Department of Natural Resources, Isfahan University of Technology, 8415683111 Isfahan, Iran; sajjad.karimi@na.iut.ac.ir (S.K.); soofiani@cc.iut.ac.ir (N.M.S.)
2. Swedish Centre for Resource Recovery, University of Borås, SE 50190 Borås, Sweden; mohammad.taherzadeh@hb.se
3. Flemish Institute for Technological Research, VITO NV, Boeretang 200, B 2400 Mol, Belgium

* Correspondence: amir.mahboubi_soufiani@hb.se; Tel.: +46-33-435-46-12; Fax: +46-33-435-40-03

Received: 9 August 2018; Accepted: 11 September 2018; Published: 14 September 2018

check for updates

Abstract: Organic-rich waste and industrial by-product streams, generated in enormous amounts on a daily basis, contain substantial amounts of nutrients that are worthy of recovery. Biological conversion of organic-waste streams using filamentous fungi is a promising approach to convert nutrients into value-added bioproducts, such as fungal biomass. High-protein fungal biomass contains different kinds and levels of amino acids, fatty acids, immunostimulants, antioxidants, pigments, etc., which make it a potential choice for application in animal feed supplementation. Considering the challenges long faced by the aquaculture industry in fishmeal production due to the increasing prices and environmental concerns, the aquaculture industry is forced to provide alternative protein-rich sources to replace conventional fishmeal. In this review, the possibilities of utilization of filamentous fungi biomass cultivated on organic-rich waste streams, as an alternative nutrient source in fish feed, were thoroughly reviewed.

Keywords: Organic-rich waste; nutrient recovery; fungal biomass; fish feed formulation; proximate analysis

---

1. Introduction

As a consequence of population growth and changes in living standards, various industries have grown in production size to meet the demands. This has resulted in an extreme increase in the amount of different wastes generated throughout the world. Many municipal and industrial waste and by-product streams, mainly from food-related industries, contain substantial amounts of carbohydrates, lipids, proteins, inorganic compounds, and large quantities of water. Environmental problems associated with organic-rich waste handling and disposal, in addition to the scarcity of virgin resources, have long been a matter of concern. Therefore, it is essential that these organic-rich waste streams are treated efficiently in order to recover their nutrients and/or convert them into value added products, and mitigate their environmental impact [1]. Nutrients can be recovered from waste streams through different extraction and/or conversion approaches such as biological treatment [2]. In this regard, a variety of different microorganisms, including bacteria, yeast, and filamentous fungi, are applied in order to biologically treat the organic wastes [3].

Among the different microorganisms used for bioconversion processes, filamentous fungi have received great attention in industrial scale production of various value-added products such as enzymes, pigments, organic acids, and other metabolites [4,5] as they can grow on various organic-rich substrates [6]. In order to decrease the costs of large-scale production of fungal products and to alleviate environmental impacts of industrial wastes, utilization of industrial byproduct/wastes as fungal cultivation media has recently attracted great research attention. Production and secretion of several different enzymes such as proteases and lipases have enabled filamentous fungi to degrade, consume, and thrive on different substrates [4,7]. Filamentous fungi can also be the source of metabolites such as ethanol and carboxylic acids, pigments, and antibiotics [5,8,9]. In addition, as fungal biomass is rich in proteins, fatty acids and vitamins, it makes a potentially suitable human food and animal feed source. Traditionally, fungal fermented human food, such as miso, tofu, and tempeh are used in eastern and southeastern Asian countries like Japan, China, and Indonesia [10]. Accordingly, the nutrient constituents of fungal biomass make it a promising source for supplementation or replacement of conventional animal feed such as fish feed.

In fish cultivation, the production is directly related to the supply of nutrients through fish feed [11]. While the feeding cost is greatly dependent on the fish intensity, under intensive and semi-intensive aquaculture conditions, the feeding imposes 30%–60% of the total production costs [12]. In order to maintain fish growth and health, fish diets should contain adequate levels of protein [13,14]. Due to the high protein content, palatability and digestibility, and balanced amino acid profile, fishmeal is the preferred choice of protein source in conventional fish diets [15]. Fishmeal is a costly ingredient in fish feed as it is in high demand by other animal culturing industries [16]. The high price and scarcity of fishmeal is challenging the expansion of local and international fish farming and aquaculture industries. It is noteworthy that fishmeal prices have risen from 350 USD per ton in 2000, to 1600 USD per ton in 2017 [17]. On the other hand, in order to meet the demands, fish production through aquaculture has doubled since 1985 by hitting 170 million tons in 2017 [17]. Therefore, as the aquaculture industry expands, the demands for fishmeal increase and so do the prices. Adding to that is the intensive catches made from the seas and oceans, which imposes adverse effects on fish stock in the pelagic zone of the natural water bodies [11,18]. Therefore, in order to move toward a more sustainable aquaculture, it is of great importance to seek a renewable and cheap supplementation source that partially or totally replaces fishmeal.

Based on the nutritional compatibility with fishmeal, different animal, plant, and microorganism-based sources have been evaluated as a replacement for fishmeal [11,19]. Among the microbial sources, fungal biomass cultivated on various low-value waste and by-product streams can be one of the most promising supplements to fish feed [20,21]. Filamentous fungi, with high protein content, desirable amino acid profile, immunostimulants, pigments, and antioxidants can also be nominated as an alternative to fishmeal.

This review investigates the possibilities of applying filamentous fungi biomass cultivated on organic-rich waste and by-product streams as a fish feed supplement. In this regard, the potential of filamentous fungi in recovering nutrients from waste streams is evaluated, and desirable nutritional characteristics of fungal biomass that make them good candidates for fishmeal replacement are assessed. Moreover, further information regarding the nutritional requirements of fish are thoroughly discussed in this review (Figure 1).

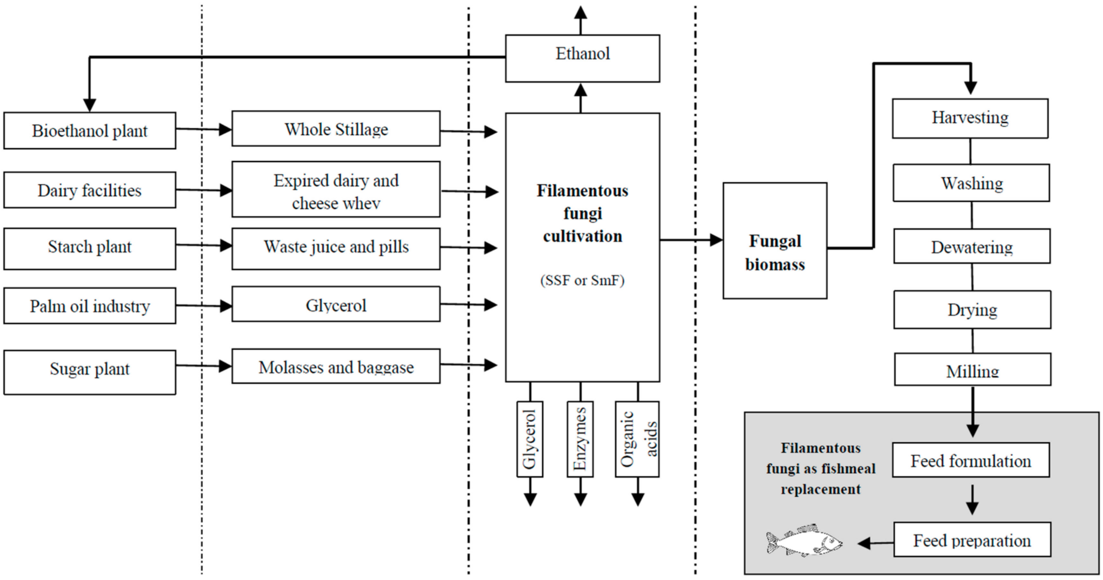

Figure 1. Overall scheme of potential industrial waste/by-product biorefinery, using filamentous fungi cultivated in submerged fermentation (SmF) or solid-state fermentation (SSF) for the production of value-added products such as enzymes, organic acids, ethanol, glycerol, and protein-rich fungal biomass for fish feed.

2. Filamentous Fungi

Fungi are one of the largest groups of eukaryotes and are classified as a separate kingdom from plants, protists, animals, and bacteria. It is estimated that there are about 2.2–3.8 million species of fungi, of which only 120,000 have been identified [22]. Fungi have been classified into four separate groups of *Chytridiomycota*, *Zygomycota*, *Ascomycota*, and *Basidiomycota* [10]. Filamentous fungi are branched multicellular fungi (referred to as "Dikarya"), consisting of thread-like elongated structures called hyphae [23].

2.1. Filamentous Fungi Cultivation

Filamentous fungi have the ability to thrive on various substrates by degrading complex carbohydrates, lipids, and proteins into simpler sugars, fatty acids, and amino acids, respectively, using their complex enzyme machinery [7]. The output of these bioconversion processes are metabolites such as organic acids, bioethanol, etc., along with high-quality fungal biomass [24].

Filamentous fungi can be cultivated under submerged fermentation (SmF) and solid-state fermentation (SSF) culture conditions. In both SmF and SSF cultivation approaches, the medium supplies nutrients for fungal growth, and any changes in the medium composition affects the metabolites and biomass yield and quality [25]. While defined synthetic media such as glucose and sucrose are popular with biologists, as they allow for accurate control of changes in the media composition, they are costly [26]. The high cost of synthetic media has motivated the search for new media formulations from inexpensive by-products and wastes, which are able to support and fulfill nutritional requirements for microbial growth [27]. Substrates used for fungal cultivation should be easily biodegradable, cheap, easily available, and contain sufficient required micro and macro-nutrients [28]. Organic-rich industrial by-products and waste streams such as bioethanol, dairy, and starch production industries may meet these requirements for feasible fungal cultivation (Table 1) Mahboubi et al. [29] used different dairy wastes and by-products as substrates for cultivation of edible filamentous fungi *Aspergilus oryzae* and *Neurospora intermedia*. Many strains of filamentous fungi from genera such as *Neurospora*, *Rhizopus*, and *Aspergillus* that secrete amylases can perform simultaneous saccharification and fermentation (SSF) on starchy substrates and various crops [30,31]. Soybean, rice, grains, legumes, potato, corn stover, wheat bran, and other agricultural and forestry (lignocellulosic material) residues have been used for the production of various fungal metabolites and enzymes [10,24,32–35]. Lignocellulosic residues [36], spent sulphite liquor from the pulp and paper industry [37], stillage from the bioethanol production industry [35], molasses (from sugar cane and sugar beet), sucrose [38], and starch-based effluents [39] have also been studied as potential fungal cultivation media.

The techno-economy of the application of filamentous fungi in the treatment of industrial by-products has been considered in different research studies. Rajendran et al. [40] studied the techno-economy of the integration of first and second-generation bioethanol production by the cultivation of filamentous fungi on by-product streams of stillage and wheat bran. They reported that although the integrated process imposed greater capital costs than only fungal cultivation on stillage, it could result in up to 48% increase in the net present value (NPV). In another work, Souza Filho et al. [41] performed a technical and economical evaluation, and a life cycle assessment (LCA) on the production of filamentous fungal biomass from potato liquor, a by-product of potato starch production. This research focused on different treatment scenarios for heat-treated potato liquor, with one including the application of final fungal biomass as a fish feed supplement.

Table 1. The general composition of some of the organic-rich waste and by-product streams mentioned in this review.

	Whole Stillage [42]	Thin Stillage [42]	Wheat Starch Plant Wastes [43]	Potato Protein Liquor [37]	Expired Milk [29]	Vinasse [21]
pH	4.3	3.5	5.2	5.3	5.5	4.3
Total solid (% *w*/*w*)	15.6	77.5	28.5	43.8	11	2.2
Suspended solid (% *w*/*w*)	8.8	26	3.7	0.9	-	1.5
Ash (% *w*/*w*)	3.2	10	1.9	11.4	-	-
Fat	-	-	-	-	3	-
Crude protein (% *w*/*w*)	32	4.4	1.2	20.2	3	36.5
Saccharides (g/L))	23.1	21.7	3.8	73.9	50	-
Acetic acid (g/L)	0.4	-	1	-	-	0.8
Glycerol (g/L)	12	7.6	0.2	-	-	6.8
Lactic acid (g/L)	1.7	11.6	1.2	-	4.9	7.4

(As changes in the composition of organic-rich waste and by-products commonly occur, the values presented in the table are the average values provided by the cited literature).

2.2. Filamentous Fungi Metabolic Activity

During cultivation, fungi utilize the substrate's nutrients, and depending on the cultivation conditions, produce a variety of metabolic products such as bioethanol and organic acids. Bioethanol is one of the metabolites produced by filamentous fungi during fermentation. *Rhizopus* sp. and *Mucor* sp. are two major genera used for the production of ethanol and organic acids [38]. *Neurospora* spp. and *Fusarium* spp. have also been applied for ethanol production on various waste streams including thin stillage, whole stillage, and lignocellulosic materials [4,44].

The type (amylases, cellulases, pectinases, proteases, phytase, lipases, tannases, urease, etc.) and concentration of enzymes secreted by filamentous fungi is dependent on the fungal species and the cultivation condition [45]. *Rhizopus* and *Aspergillus* are both well documented as producing amylases and glucoamylases. In addition, the proteolytic activity is largely demonstrated in filamentous fungi, for instance, pepsin and renin have been extracted from zygomycetes such as *Rhizomucor* and *Mucor* [46]. Moreover, it has been reported that *Rhizopus oligosporus* can produce two types of phytases during solid-state cultivation [47]. In addition, cellulases, xylanases, and β-glucosidases can be produced by *Fusarium* spp., *Rhizopus microsporus*, and *R. oligosporus*, respectively [7,24,48].

Other interesting metabolites produced by filamentous fungi are organic acids that have wide applications, mainly in the food industries [31]. Among organic acids, lactic acid is one of the most abundant and has various applications in the food, leather, cosmetics, and pharmaceutical industries [34]. Compared to bacteria, *Rhizopus* strains can produce lactic acid using cheaper substrates [7]. Citric and fumaric acids are the other main fermentation metabolites produced by filamentous fungi [49–51]. Currently, *Aspergillus niger* is largely applied for citric acid production using sugarcane molasses, glucose, and sucrose as cultivation substrates [34]. Fungal fumaric acid is used as a food additive, in production of resins and biodegradable polymers [50]. Moreover, *A. niger* and other *Aspergillus* spp. are used for the production of gluconic and itaconic acids, respectively [52].

Different species of filamentous fungi have long been used for the production of fermented human food; therefore, they are categorized as GRAS (Generally Recognized as Safe) microorganisms [4,7]. For example, *A. oryzae* is used for the production of native Japanese foods such as sake, shoyu, and miso [53]. Additionally, *N. intermedia* is used for the production of the Indonesian food oncom—a soybean-based cake [33].

2.3. Filamentous Fungal Biomass

Apart from the aforementioned fungal products, fungal biomass contains substantial amounts of proteins, fats, amino acids, and carbohydrates (e.g., chitosan and chitin) that make it a potential candidate for animal feed supplementation [50,54]. One of the factors that may limit the application of fungal biomass as mammalian food is its high content of nucleic acids (NA), which may cause an increase in plasma uric acid in the long-term, leading to gout and kidney stone formation [55]. However, fish species such as salmonids have the ability to produce high levels of active liver uricase that enables them to metabolize NA without health risks [56].

In order to maintain fungal biomass for further use as food and feed, fungal biomass has to be properly harvested and processed. Different approaches are needed in order to extract and purify metabolites, enzymes, and biomass. These methods are different for SSF and SmF. For SmF biomass production after cultivation, harvesting, washing, dewatering, drying, and milling should be performed (Figure 1). Filamentous fungi has a high moisture content, so dewatering may be useful to reduce the drying time, energy, and transportation needs. Through the biomass drying process, the moisture content is reduced to under 8% and the spoilage threat is minimized [57]. In order to use dried filamentous fungi as fishmeal, it should be milled and stored in a cool, dry place without direct exposure to sun light until use [58].

3. Fish Feed

In general, fish dietary requirements include protein, lipids, carbohydrates, vitamins, and minerals that are necessary for growth, reproduction, and other typical physiological functions. These dietary requirements vary by fish species, age, life cycle stage, sex, and environmental conditions. In the natural habitats, fish feed on naturally existing sources such as terrestrial plants (especially fruits and seeds), aquatic plants (microalgae and macrophyte) [59], terrestrial invertebrates (e.g., Hymenoptera, Coleoptera, Hemiptera, Orthoptera, and Homoptera) [60], zooplanktons (e.g., Rotifera, Artemia and Copepoda) [61], and zoobenthos (e.g., Chironomidae and Ephemeroptera) [62]. However, for cultured fish and especially under intensive and semi intensive conditions, feed should be supplied artificially. Protein is the most important ingredient contributing to growth in fish diets and accounts for 40–60 percent of the total fish production cost [63]. Conventionally, in fish farming, fishmeal has been the protein source in fish diet.

3.1. Fishmeal

Fishmeal is a highly digestible protein source that is being used as fish and shrimp feed [64]. Fishmeal is a flour-type material with a high protein, lipid, minerals, and vitamin content, which is obtained after drying and milling fish or fish parts (fish trimmings or other fish processing by-products) [65]. High quality fishmeal contains 61%–73% crude protein (dry weight) and composes between 30%–45% of the fish feed weight. The low content of alimentary inhibitors or anti-nutrient factors and high palatability of fishmeal allows for complete and fast ingestion of feed that lead to a decrease in nutrient leaching [66]. The amino acid profile of fishmeal, especially essential amino acids (EAA), defines the essentiality of the application of fishmeal in the feed (Table 2). The quality of each feed protein source is determined by the amino acid composition and digestibility of the protein, healthiness of the raw material, and maintenance conditions [67]. Despite oil extraction during fishmeal production process, fishmeal contains 4%–20% oil [67]. Fish oil is highly digestible and contains polyunsaturated fatty acid (PUFA) of both omega 3 and omega 6, such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) that make it a profitable energy source for fish (Table 3) [66]. Additionally, PUFA can strengthen the fish's immune system against pathogens, while reducing stress responses [68].

Table 2. Crude protein (CP), ash content and percentage of essential amino acids (% dry weight) for different protein sources.

Essential Amino Acids	Fishmeal [58]	Soybean Meal [58]	Rendered Meat Meal [58]	Poultry By-Product Meal [58]	Blood Meal [58]	Fungal Biomass [21]
CP%	64.6	47.5	54.0	64.1	77.1	-
Ash%	15.0	6.0	25.0	19.0	4.4	-
Arginine	3.8	3.7	6.2	6.2	4.3	3.9
Histidine	1.5	1.2	2.1	1.9	6.6	1.3
Isoleucine	2.7	2.1	2.9	3.1	1.2	2.0
Leucine	4.5	3.6	7.1	6.1	14.3	3.1
Lysine	4.7	3.1	5.7	5.2	9.1	2.9
Methionine	2.3	1.4	1.5	1.7	1.3	0.6
Phenylalanine	4.4	4.2	4.0	3.5	6.9	3.0
Threonine	2.3	1.9	3.7	3.4	5.3	2.8
Tryptophan	0.6	0.7	0.7	1.4	1.4	0.1
Valine	2.8	2.6	4.9	3.9	9.1	2.1

(The values presented in the table are the average values provided by the cited literature).

Table 3. Fatty acids content of various sources (g/100 g of total FA).

Fatty Acids	Anchovy [69]	Sardine [69]	Herring [69]	Linseed oil [69]	*Mucor* sp. [70]	*Rhizopus* sp. [70]	*Aspergilus flavus* [71]
C14:0	7.2	7.6	6.2	0.1	0.1	0.1	-
C16:0	17.8	16.2	12.7	6.1	8.9	9.7	14.9
C16:1	9.8	9.2	7.5	0.1	-	-	0.5
C18:0	3.9	3.5	1.1	3.4	4.6	5.8	10.5
C18:1	12.0	11.4	12.9	18.8	24.5	29.6	35.8
C18:2n-6	1.1	1.3	1.1	16.3	60	54.3	34.3
C18:3n-3	0.8	0.9	0.7	54.4	2	-	0.8
C18:4n-3	2.4	2.0	1.4	-	-	0.5	-
C20:1	1.9	3.2	15.1	-	-	-	0.6
C20:4n-6	0.3	1.6	0.3	-	-	-	-
C20:5n-3	18.3	16.9	6.8	-	-	-	-
C22:1	1.4	3.8	22.0	-	-	-	-
C22:5n-3	1.5	2.5	0.8	-	-	-	-
C22:6n-3	8.5	21.9	5.8	-	-	-	-
∑n-3	31.5	44.2	15.5	54.4	-	-	-
∑n-6	1.4	2.9	1.4	16.3	-	-	-
n-3/n-6	22.5	15.2	11	3.3	-	-	-

(The values presented in the table are the average values provided by the cited literature).

3.2. *Alternative Fishmeal Replacements*

Fishmeal is mainly produced from pelagic fish species such as anchovy, sardine, menhaden, and herring living in the seas and oceans [57]. In the last few decades, harvesting fish species that are used for fishmeal production has reached its maximum capacity, leading to an increase in fish and fishmeal prices [72]. With regard to the current fishmeal production volume and projected aquaculture growth, aquaculture is heading toward a severe "fishmeal" bottleneck [11,73,74], which calls for an alternative protein source replacement.

3.2.1. Plant-Based Sources

Due to high availability and low price, plant-based protein sources were the first choices as fishmeal replacement [63]. Different plant protein sources such as soybean meal, rapeseed meal, canola meal, pea, rice, wheat, corn gluten, and lupine have been used as alternative sources for fishmeal [66,75]. However, plant-based protein sources contain a high level of anti-nutritional factors (ANFs) such as protease inhibitors, phytic acid, glocosinolats, saponins, lectin, phytostrogens, sinapinic acids, and phenolic compounds that deteriorate fish health [75]. While the ANF concentrations can be reduced in the feedstuff by using various techniques such as heat treatments as well as chemical and organic solvents, these procedures are expensive, time consuming, and in some cases decrease protein solubility and yield [76]. Utilization of plant-based protein sources is also limited due to: Low palatability; low digestibility; low content of some required amino acids such as methionine, tryptophan, arginine, and threonine [77]; high fiber content; and non-starch polysaccharides [75]. These shortcomings result in a reduction in growth performance and feed efficiency, increase in nitrogen excretion and water pollution, and alteration in gut microbiota [78,79]. Intestine structure and functional changes such as shorter posterior gut folds, intestine enteritis, and higher level of uptake of substances that are not normally absorbed, engrossed lamina-propria and submucosa that interfere in gut health, have been reported as side effects of using plant-based protein [80,81]. Detrimental effects on non-specific immune systems, anti-oxidant capacity, and disease resistance are the other problems affiliated with the replacement of fishmeal with plant-based protein sources [82]. Additionally, direct use for human consumption is another constraint on the use of plant protein material for fish feed [72]. All the above-mentioned concerns act as limiting factors for the high inclusion of plant-based protein in fish diet.

3.2.2. Animal-Based Sources

Animal-based protein sources including meat meal, bone meal, blood and feather meal, and poultry byproducts have been used as fishmeal replacements. However, the high cost and unfavorable properties of these protein sources limit their application in fish diets [63]. Compared to fishmeal, meat meal, bone meal and poultry byproduct have lower protein digestibility and higher ash content that interfere with intestinal absorption of nutrients and trace elements such as zinc [83]. Blood and feather meal have poor digestibility, and their amino acid profile is incompatible with fish requirements [84].

3.2.3. Microbial-Based Sources

Microbial-based protein sources including both whole microorganism and different byproducts from bacteria, algae, and fungi can be used as single cell protein (SCP) for fishmeal replacement [23]. These microorganisms if used as fish feed, not only do they not compete with human food sources, but they also enhance feed availability [19]. The nutritional properties of filamentous fungi from a fish feed application viewpoint is discussed in the following sections.

Protein

The protein content of fungal cell differs depending on the fungal species and cultivation related factors (Table 4). Commonly, zygomycetes and ascomycetes contain around 40%–50% crude protein [45]. The final protein content of fungal biomass is influenced by the cultivation medium. The nitrogen content of cultivation media directly effects the fungal protein yield [21]. Aside from the fungal cultivation media, the fungal cell protein content is also dependent on the harvesting, dewatering, and drying approaches [85].

The amino acid composition is used as a good criterion to compare protein quality. Moreover, the ratio of essential and nonessential amino acids has a particular importance [86]. As has been reported in the literature, the amino acid profile of filamentous fungal biomass is compatible with that of fishmeal protein [21]. However, as the knowledge on the biomass amino acid content of different fungal species is limited, this claim cannot be generalized. As shown in Table 2, except for methionine, lysine, and tryptophan, a sufficient amount of other EAAs is provided in *Rhizopus oligosporus* biomass. Zygomycetes have previously been examined for their amino acid production capabilities. For example, *R. oligosporus* cultivated on thin stillage had considerable concentrations of arginine, aspartic acid, cysteine, phenylalanine, glutamic acid, histidine, isoleucine, leucine, lysine, proline, serine, tyrosine, and valine [87]. The amounts of amino acids were similar, or in the case of methionine, more than those reported for soybean meal (the most important alternative source for fishmeal) [87]. Nitayavardhana et al. [21] reported that *R. oligosporus*, cultivated on vinasse, contained around 50% protein and had an amino acid profile comparable to those of fishmeal and soymeal. High protein content and amino acid profile compatibility with fishmeal show the potential of fungal biomass as a sustainable nutritional replacement in fish feed.

Table 4. Protein content of different filamentous fungi species.

Fungal Strain	Substrate	Protein Content (% *w/w* Dry Weight)	Ref.
Aspergillus oryzae	Palm oil waste	39	[88]
Rhizopus oligosporus	Starch processing wastewater	46	[89]
Rhizopus sp.	Spent sulphite liquor	50–60	[90]
Mucor circinelloides	Corn ethanol stillage	30.4	[91]
Pythium irregulare	Corn ethanol stillage	28	[30]
Rhizopus, Mucor, Rhizomucor	Isolated from Tempe	47–63	[92]
Mucor indicus *Rhizopus* sp.	Spent sulphite liquor	30–50	[10]
Rizhopus oryzae	Vinasse	49.7	[21]
Neurospora intermedia		56	
Aspergillus oryzae	Thin stillage	48	[93]
Rhizopus sp.		55	
Rhizopus oligosporus	Corn ethanol stillage	43	[94]
Aspergillus oryzae *Neurospora intermedia*	Stillage	43	[95]
Rhizopus oligosporus	Wheat bran	40	[96]
Neurospora intermedia *Aspergillus oryzae*	Dairy waste	40	[29]
Neurospora intermedia	Lignocellulose	50	[20]

(The values presented in the table are the average values provided by the cited literature).

Lipid

Lipids can be classified into different groups of free fatty acids, steroids, sphingolipids, glycolipids, neutral lipids, and phospholipids [58]. These compounds have important structural and functional duties in the fungal cell membrane and are one of the main energy sources for cell metabolism. Fungi can produce and secrete lipases that have the capacity to degrade substrate lipids and oils and produce free fatty acids and glycerol from triacylglycerols (TAG) [97]. Mitra et al. [91] and Liang et al. [30] described the ability of different fungal species in valuable nutritional oil production. Apart from the protein content, the fungal biomass contains 20%–25% oil [98]. The lipid content of fungal biomass is dependent on the species and cultivation conditions. When the N:O ratio becomes too low, fungal cells begin accumulating lipids in their intracellular space [99]. A range of four to 19 different fatty acids can be extracted from filamentous fungi, mostly comprised of 12 to 24 carbon chain length [98]. Fatty acids in filamentous fungi are typically structured in membrane phospholipids and storage triacylglycerol including palmitic and stearic acids, and other unsaturated fatty acids such as palmitoleic, oleic, linoleic, and linolenic acids [54]. The relative concentration of a single fatty acid can be from less than 1%, to more than 75%, in comparison with the total fatty acid content in fungal biomass [54]. The fat content of fungal cell is dependent on the fungal species (Table 3). For instance, oleaginous fungi produce a high amount of TAG [99]. PUFAs, especially linoleic acid

(18:2n-6) and α-linolenic acid, are two of the most important fatty acids that should be included in fish diet. These fatty acids and others such as arachidonic acid (20:4n-6) are needed for central nervous system (CNS) functions [13]. Furthermore, these fatty acids are required for longer chain PUFAs synthesis such as decosahexanoic acid (22:6n-3) and eicosapentanoic acid (20:5n-3). In general, fish oil and other oil sources that are used in fish feed are responsible for the delivery of lipids and fatty acid requirements of fish. Therefore, the addition of fungal biomass containing valuable fatty acids to fish diet can benefit the overall growth and health of the fish.

Immunostimulants

Prevention of fish disease outbreak is a critical subject in aquaculture and has great effects on the final fish yield, product quality, and consumer preferences [74,100]. In the last few decades, antibiotics and other medicines such as chloramphenicol, nitrofuran, oxytetracycline, malachite green, copper alloys, methylene blue, etc. have been used frequently in order to prevent fish diseases (bacterial and viral disease) and also to promote growth [101,102]. The use of antimicrobials in fish culture increases the selective pressure on pathogens and causes bacterial strains to develop resistance. While some new techniques such as vaccination are developed in order to control fish diseases, these approaches are expensive and laborious [103]. Furthermore, when the case is hatchery practices, conventional immunization methods are often not as efficient as expected.

Prevention of disease outbreak can be reached by enhancing animal innate and specific immunity system, either at the cellular or humoral levels. Immunostimulants have the potential to be used as an alternative preventive and curative treatment techniques against fish related diseases. In order to enhance the defense mechanisms in animals, several immunostimulants compounds such as chitin, chitosan, β-glucan, and mannan oligosaccharide have been suggested [104]. Several studies demonstrated the immunostimulants activity of levamisole, β-glucan, peptidoglycan, chitin, and chitosan [101,105–110]. The fungal cell wall is a complex structure of 80%–90% polysaccharides [111]. While the cell wall differs greatly in composition among fungal species, it generally comprises 15%–30% of the fungal cell mass [112]. The most frequent components found in filamentous fungi cell wall are glucans (30%–80%), chitin and chitosan (1%–15%), mannans and/or galactomannans, and glycoproteins [113]. These compounds are present in mycelia, stalks, and spore tissues [114].

The first defense mechanism that fish employ against all type of pathogens is their innate immune system [115]. Dietary administration of immunostimulants such as β-glucans, mannan oligosaccharids, chitin, and chitosan have been greatly accepted to enhance the immune system capabilities, stress related responses, and resistance to diseases in marine and freshwater fish species [116]. Immunomodulatory active components increase the production of anti-bacterial peptides, such as lysozyme and the phagocytic activity of macrophages. Increasing lysozyme activity and innate immunity has been reported in sea bass, *Dicentrarchus labrax* [117], nile tilapia, *Oreochromis niloticus* [118], *Epinephelus bruneus* [119], rainbow trout, *Oncorhynchus mykiss* [103], olive flounder, *Paralichthys olivaceus* [120], and *Cirrhina mrigala* [121], which were fed on β-glucan, chitin, and chitosan. Considering the filamentous fungi cell wall immunostimulant content, dietary administration of filamentous fungi as fishmeal replacement can lower the application of medicines and antibiotics, and enhance fish health and resistance against bacterial and viral pathogens.

Pigments

In recent decades, pigments have attracted a great deal of research interest due to their exceptional biological roles (anti-oxidative, free radical killing, anti-carcinogenic, immunostimulation, protection against viruses and bacteria) [122,123]. Filamentous fungi are introduced as potential pigment producing microorganisms [124]. They produce a wide range of pigments such as carotenoids, melanins, flavins, phenazines, quinones, and sometimes monascins, violacein or indigo [9,125]. *Aspergillus* sp. together with other ascomycetes such as *Neurospora* sp., *Fusarium* sp. and *Penicilium* sp. have been reported to produce various pigments [123–125]. Currently, a number of different types of pigments from filamentous fungi such as lycopene, β-carotene, astaxanthin, canthaxanthin, lutein, and capxanthin are produced commercially and supplied to the market [125]. Moreover, red and yellow pigments from *Monascus* sp. are produced in large scales and used as food colorant [85].

Different pigments are advantageous to fungi by helping them to protect themselves against undesirable environmental conditions. For example, carotenoids promote protection against dangerous ultraviolet waves, melanin helps to control the stress related to changes in the environmental conditions and flavin acts as a cofactor for enzyme catalysis [125].

Fish, like other animals, are not able to produce *de novo* carotenoid, and their color is totally dependent on pigment input from the diet [126]. The quality of flesh coloration is one of the most notable criteria that can have a significant influence on the fish market. In recent years, apart from carotenoids' role in muscle pigmentation, increasing attention has been paid to other roles, e.g., in growth promotion [127], improvement of brood-stock performance [78], antioxidant properties [128], immune functions [129], and resistance to diseases [100,130]. In addition, carotenoids, as precursors of transcription regulators, have important roles in vision [131–134]. In various fish species, body color can affect mate selection and social interactions such as dominance hierarchies [135]. In addition, some fish species benefit from dynamic color patterns to communicate with one another [136]. The flesh and skin color of cultured fish may be weaker compared to the wild type due to the natural diet composition or husbandry practices [135]. Accordingly, flesh color of cultured fish is enhanced by using synthetic pigments (β-carotene, canthaxanthin, zeaxanthin, and astaxanthin) and/or natural pigments (algae, higher plants, and crustacean meal) [127,137]. Currently, almost all pigments supplemented to fish feeds come from synthetic pigments. However, synthetic pigments are expensive, and if not applied in appropriate concentrations, can be toxic to fish. Synthetic pigments such as astaxanthine, zeaxanthin, and β-carotene have been used in the last few decades for enhancing the fillet and/or skin color [138]. Filamentous fungi, as a supplement in fish feed, can be a source of natural pigments. Therefore, in addition to having positive effects on fish physiology, fungal biomass supplementation can reduce the final feed cost and solve the problems arising from the high dosage of synthetic pigments [68,135].

Antioxidants

In many living organisms, the presence and accumulation of nitrogen and oxygen free radicals can cause general health deterioration by damaging structural lipids, proteins, and DNA [139,140]. Normally, animals employ natural mechanisms to mitigate the effects of free radicals; however, the level of antioxidants produced naturally may not always be adequate enough [141]. Filamentous fungi are a well-known source of antioxidants such as ergothionein, phenolic acids, flavonoids, tocopherols, ascorbic acid, carotenoids, polyketides, terpenes, and steroids [142,143]. Methanolic extracts found in *M. purpureus* have robust activity against free radicals and lipid peroxidation [144]. Commonly, both natural antioxidants such as vitamin A, C, and E, pigments including carotenoids, and synthetic antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxyltoluene (BHT) have been used as antioxidant agents in fish feed [58]. Utilization of natural antioxidant compounds by adding filamentous fungi meal to fish feed can potentially improve the health status in fish and aquatic animals. Using filamentous fungi biomass as the potential natural antioxidant source in fish feed can also reduce the cost of synthetic antioxidant supplementation and also result in environmental benefits [145].

Vitamins

While vitamins are vital for correct physiological and metabolic functions, animals cannot synthesize them [58]. Microorganisms such as filamentous fungi, as plants, are able to synthesize these components. Some of the water-soluble vitamins such as C (ascorbic acid), B_6 (pyridoxine), B_2 (riboflavin), nicotinic acid, and nicotinamide are synthesized by filamentous fungi. There are reports on the production of pantothenic acid (B_5) and β-carotene (pro-vitamin A) by *Fusarium* sp.

and *Neurospora* sp., respectively [45]. Fish, as with other animals, need to be supplied by exogenous vitamins, and fungal biomass that can provide the dietary vitamin needs of fish.

3.3. Challenges in the Application of Fungal Biomass as Fish Feed Supplement

In addition to the specific cell structure differences of various fungal species, other factors such as culture conditions, cultivation media, etc. contribute to the final composition of fungal biomass [146]. These differences in the protein, lipid, vitamin, pigment, etc. of fungal biomass challenge the introduction of a standardized method for their application in fish feed.

As a number of filamentous fungi strains in genera such as *Aspergillus*, *Fusarium*, *Monascus*, *Neurospora*, and *Rhizopus* are categorized as GRAS by the United States Food and Drug Administration (USFDA), their application as animal feed and even human food is allowed [7]. However, different measures should be taken into consideration when applying them as a fish feed supplement.

Filamentous fungi may produce mycotoxins such as aflatoxin, ochratoxin, citrinin, and fusarin [147]. Therefore, special attention must be paid to prevent the inclusion of mycotoxins as an ingredient in fish feed. In addition, a number of fungal species, including *Fusarium*, *Aspergillus*, *Exophiala*, *Scytalidium,* and *Mucor* have been isolated as opportunistic filamentous fungal pathogens from various fish and shellfish species such as Atlantic salmon (*Salmo salar*) and rainbow trout (*Onchorhynchus mykiss*) [148]. Considering the problems pointed out related to fungal mycotoxins and pathogenicity, it is critical that the fungal biomass that is to be used in fish feed is properly dried and treated prior to application as a fish feed supplement.

Another issue with the application of fungal biomass cultivated on waste streams is that filamentous fungi are highly tolerant to xenobiotic compounds present in waste streams. The high efficiency of filamentous fungi in absorption and adsorption of various environmental pollutants has introduced them as a low cost bioremediation solution [149]. Different species of white rot fungi have been used for removal of various types of pollutants such as phenols [150], polycyclic aromatic hydrocarbons [151], dyes [152], and heavy metals such as lead and cadmium [153]. Kapoor et al. [154] successfully removed different heavy metal ions including lead, cadmium, copper, and nickel from the culture media using *A. niger*. In another study, Delgado et al. [155] used *Fusarium* sp. for the removal of nickel, cadmium, and copper from wastewater. Therefore, in order to prevent xenobiotic compounds such as heavy metals from reaching our dining tables through fish fed with filamentous fungi, it is imperative to assure that fungi has been cultivated on by-product and waste streams with no health threatening compounds.

4. Conclusions

The application of filamentous fungi biomass as a potential replacement to fishmeal and nutritional supplement to fish feed can remediate some of the shortcomings confronted in the advancement of the fish aquaculture industry. Moreover, production of value-added bioproducts through fungal bioconversion of organic-rich by-product and waste streams opens new horizons for sustainable nutrient recovery. The high protein, fatty acids, pigments, and immunostimulants content of fungal biomass can contribute to the nutrient quality of fishmeal. If this highly nutritious fungal biomass source is provided through bioconversion of nutrient-rich waste and by-product streams, the environmental burdens imposed by these wastes are alleviated, and these negatively-valued streams are converted into value-added products that can boost regional and international economy. However, it is noteworthy that as the biomass obtained from the different fungal strains differ in amount and type of constituents, standardization of the application of fungal biomass in fish feed still requires extensive research work.

Author Contributions: Conceptualization, S.K., A.M., N.M.S. and M.J.T.; Investigation, S.K. and A.M.; Methodology, S.K. and A.M.; Project administration, N.M.S. and M.J.T.; Supervision, N.M.S. and M.J.T.; Writing—original draft, S.K. and A.M.; Writing—review & editing, A.M., S.K., N.M.S. and M.J.T.

Funding: This research was funded by Lantmännen Agroetanol (Sweden), Swedish Agency for Economic and Regional Growth and European Regional Development Fund grant number 20201656.

Acknowledgments: The authors would like to express their gratitude to the European Regional Development Fund "Waste2Taste," Lantmännen Agroetanol (Sweden), and Isfahan University of Technology (Iran) for their technical and financial support of this work.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Dahiya, S.; Sarkar, O.; Swamy, Y.V.; Mohan, S.V. Acidogenic fermentation of food waste for volatile fatty acid production with co-generation of biohydrogen. *Bioresource Technol.* **2015**, *182*, 103–113. [CrossRef] [PubMed]
2. Nasr, M.; Tawfik, A.; Suzuki, M.; Ookawara, S. Mathematical modeling of bio-hydrogen production from starch wastewater via up-flow anaerobic staged reactor. *Desalin Water Treat.* **2015**, *54*, 50–58. [CrossRef]
3. Liang, Y.; Wen, Z. 18-bio-based nutraceuticals from biorefining. In *Advances in Biorefineries*; Waldron, K., Ed.; Woodhead Publishing: Cambridge, UK, 2014; pp. 596–623.
4. Ferreira, J.A.; Mahboubi, A.; Lennartsson, P.R.; Taherzadeh, M.J. Waste biorefineries using filamentous ascomycetes fungi: Present status and future prospects. *Bioresource Technol.* **2016**, *215*, 334–345. [CrossRef] [PubMed]
5. Gmoser, R.; Ferreira, J.A.; Lennartsson, P.R.; Taherzadeh, M.J. Filamentous ascomycetes fungi as a source of natural pigments. *Fungal Biol. Biotechnol.* **2017**, *4*, 4. [CrossRef] [PubMed]
6. Lauryn, G.C.; Joshua, L.C.; Juliana Maria Leite Nobrega de Moura, B. Conversion of agricultural streams and food-processing by-products to value-added compounds using filamentous fungi. *Annu. Rev. Food Sci. Technol.* **2018**, *9*, 503–523.
7. Ferreira, J.A.; Lennartsson, P.R.; Edebo, L.; Taherzadeh, M.J. Zygomycetes-based biorefinery: Present status and future prospects. *Bioresource Technol.* **2013**, *135*, 523–532. [CrossRef] [PubMed]
8. Hadar, Y.; Cohenarazi, E. Chemical-composition of the edible mushroom pleurotus-ostreatus produced by fermentation. *Appl. Environ. Microb.* **1986**, *51*, 1352–1354.
9. Schüffler, A.; Anke, T. Secondary metabolites of basidiomycetes. In *Physiology and Genetics: Selected Basic and Applied Aspects*; Anke, T., Weber, D., Eds.; Springer: Berlin/Heidelberg, Germany, 2009; pp. 209–231.
10. Lennartsson, P.R. *Zygomycetes and Cellulose Residuals: Hydrolysis, Cultivation and Applications*; Chalmers Tekniska Högskola: Götenburg, Sweden, 2012.
11. Tacon, A.G.J.; Metian, M. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture* **2008**, *285*, 146–158. [CrossRef]
12. Azaza, M.S.; Mensi, F.; Kammoun, W.; Abdelouaheb, A.; Brini, B.; Kraiem, M. Nutritional evaluation of waste date fruit as partial substitute for soybean meal in practical diets of juvenile nile tilapia, oreochromis niloticus l. *Aquacult. Nutr.* **2009**, *15*, 262–272. [CrossRef]
13. Khan, N.; Qureshi, N.A.; Nasir, M.; Vandenberg, G.W.; Mughal, M.S.; Maqbool, A.; Jabbar, M.A.; Zikria, N. Effect of artificial feed on sensory attributes of flesh of indian major carps (*Labeo rohita*, *Catla catla* and *Cirrhinus mrigala*) fed in monoculture and polyculture systems. *Pak. Vet. J.* **2012**, *32*, 349–353.
14. Naz, S.; Javed, M. Growth responses of fish during chronic exposure of metal mixture under laboratory conditions. *Pak. Vet. J.* **2013**, *33*, 354–357.
15. Yildirim, O.; Acar, U.; Turker, A.; Sunar, M.C.; Kesbic, O.S. Effects of replacing fish meal with peanut meal (*Arachis hypogaea*) on growth, feed utilization and body composition of mozambique tilapia fries (*Oreochromis mossambicus*). *Pak. J. Zool.* **2014**, *46*, 497–502.
16. Kristofersson, D.; Anderson, J.L. Is there a relationship between fisheries and farming? Interdependence of fisheries, animal production and aquaculture. *Mar. Policy* **2006**, *30*, 721–725. [CrossRef]
17. FAO. *The State of World Fisheries and Aquaculture 2018*; FAO: Rome, Italy, 2018; p. 227.
18. Luo, Z.; Liu, C.X.; Wen, H. Effect of dietary fish meal replacement by canola meal on growth performance and hepatic intermediary metabolism of genetically improved farmed tilapia strain of nile tilapia, oreochromis niloticus, reared in fresh water. *J. World Aquacult. Soc.* **2012**, *43*, 670–678. [CrossRef]

19. Overland, M.; Karlsson, A.; Mydland, L.T.; Romarheim, O.H.; Skrede, A. Evaluation of *Candida utilis*, *Kluyveromyces marxianus* and *Saccharomyces cerevisiae* yeasts as protein sources in diets for atlantic salmon (salmo salar). *Aquaculture* **2013**, *402*, 1–7. [CrossRef]
20. Nair, R.B. *Integration of First and Second Generation Bioethanol Processes: Using Edible Filamentous Fungus Neurospora Intermedia*; Högskolan i Borås: Borås, Sweden, 2017.
21. Nitayavardhana, S.; Issarapayup, K.; Pavasant, P.; Khanal, S.K. Production of protein-rich fungal biomass in an airlift bioreactor using vinasse as substrate. *Bioresource Technol.* **2013**, *133*, 301–306. [CrossRef] [PubMed]
22. Hawksworth, D.L.; Lucking, R. Fungal diversity revisited: 2.2 to 3.8 million species. *Microbiol. Spectr.* **2017**, *5*. [CrossRef]
23. Nalage, D.; Khedkar, G.; Kalyankar, A.; Sarkate, A.P.; Sr, G.; Vb, B.; Khedkar, C. Single cell proteins. In *The Encyclopedia of Food and Health*, 1st ed.; Academic Press: Oxford/London, UK, 2016; pp. 790–794.
24. Shuvaeva, G.P.; Sysoeva, M.G. Xylanase of the micromycete rhizopus var. Microsporus 595: Preparation, structural and functional characteristics, and application. *Appl. Biochem. Microbiol.* **2010**, *46*, 641–647. [CrossRef]
25. Adejoye, O.D.; Adebayo-Tayo, B.C.; Ogunjobi, A.A.; Olaoye, O.A.; Fadahunsi, F.I. Effect of carbon, nitrogen and mineral sources on growth of pleurotus Florida, a Nigeria edible mushroom. *Afr. J. Biotechnol.* **2006**, *5*, 1355–1359.
26. Sezonov, G.; Joseleau-Petit, D.; D'Ari, R. Escherichia coli physiology in luria-bertani broth. *J. Bacteriol.* **2007**, *189*, 8746–8749. [CrossRef] [PubMed]
27. Andualem, B.; Gessesse, A. Production of microbial medium from defatted brebra (*Milletia ferruginea*) seed flour to substitute commercial peptone agar. *Asian Pac. J. Trop. Biomed.* **2013**, *3*, 790–797. [CrossRef]
28. Demirbas, A. Political, economic and environmental impacts of biofuels: A review. *Appl. Energy* **2009**, *86*, S108–S117. [CrossRef]
29. Mahboubi, A.; Ferreira, J.A.; Taherzadeh, M.J.; Lennartsson, P.R. Value-added products from dairy waste using edible fungi. *Waste Manag.* **2017**, *59*, 518–525. [CrossRef] [PubMed]
30. Liang, Y.; Zhao, X.F.; Strait, M.; Wen, Z.Y. Use of dry-milling derived thin stillage for producing eicosapentaenoic acid (epa) by the fungus pythium irregulare. *Bioresource Technol.* **2012**, *111*, 404–409. [CrossRef] [PubMed]
31. Zhang, Z.Y.; Jin, B.; Kelly, J.M. Production of l(+)-lactic acid using acid-adapted precultures of rhizopus arrhizus in a stirred tank reactor. *Appl. Biochem. Biotechnol.* **2008**, *149*, 265–276. [CrossRef] [PubMed]
32. Nout, M.J.R.; Aidoo, K.E. Asian fungal fermented food. In *Industrial Applications*; Hofrichter, M., Ed.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 29–58.
33. Singh, O.V.; Kapur, N.; Singh, R.P. Evaluation of agro-food byproducts for gluconic acid production by *Aspergillus niger* ors-4.410. *World J. Microbiol. Biotechnol.* **2005**, *21*, 519–524. [CrossRef]
34. Soccol, C.R.; Vandenberghe, L.P.S.; Rodrigues, C.; Pandey, A. New perspectives for citric acid production and application. *Food Technol. Biotechnol.* **2006**, *44*, 141–149.
35. Taherzadeh, M.J.; Fox, M.; Hjorth, H.; Edebo, L. Production of mycelium biomass and ethanol from paper pulp sulfite liquor by rhizopus oryzae. *Bioresource Technol.* **2003**, *88*, 167–177. [CrossRef]
36. Sues, A.; Millati, R.; Edebo, L.; Taherzadeh, M.J. Ethanol production from hexoses, pentoses, and dilute-acid hydrolyzate by mucor indicus. *Fems Yeast Res.* **2005**, *5*, 669–676. [CrossRef] [PubMed]
37. Asadollahzadeh, M.; Ghasemian, A.; Saraeian, A.; Resalati, H.; Taherzadeh, M.J. Production of fungal biomass protein by filamentous fungi cultivation on liquid waste streams from pulping process. *BioResources* **2018**, *13*, 5013–5031.
38. Sharifia, M.; Karimi, K.; Taherzadeh, M.J. Production of ethanol by filamentous and yeast-like forms of mucor indicus from fructose, glucose, sucrose, and molasses. *J. Ind. Microbiol. Biotechnol.* **2008**, *35*, 1253–1259. [CrossRef] [PubMed]
39. Jasti, N.; Khanal Samir, K.; Pometto Anthony, L.; van Leeuwen, J. Converting corn we-tmilling effluent into high-value fungal biomass in a biofilm reactor. *Biotechnol. Bioeng.* **2008**, *101*, 1223–1233. [CrossRef] [PubMed]
40. Rajendran, K.; Rajoli, S.; Taherzadeh, M.J. Techno-economic analysis of integrating first and second-generation ethanol production using filamentous fungi: An industrial case study. *Energies* **2016**, *9*, 359. [CrossRef]
41. Souza Filho, P.; Brancoli, P.; Bolton, K.; Zamani, A.; Taherzadeh, M. Techno-economic and life cycle assessment of wastewater management from potato starch production: Present status and alternative biotreatments. *Fermentation* **2017**, *3*, 56. [CrossRef]

42. Ferreira, J. Integration of Filamentous Fungi in Ethanol Dry-Mill Biorefinery. Ph.D. Thesis, Högskolan i Borås, Borås, Sweden, 2015.
43. Souza Filho, P.F.; Zamani, A.; Taherzadeh, M.J. Edible protein production by filamentous fungi using starch plant wastewater. *Waste Biomass Valoriz.* **2018**, 1–10. [CrossRef]
44. Xu, Q.; Li, S.; Fu, Y.Q.; Tai, C.; Huang, H. Two-stage utilization of corn straw by rhizopus oryzae for fumaric acid production. *Bioresource Technol.* **2010**, *101*, 6262–6264. [CrossRef] [PubMed]
45. Archer, D.B.; Connerton, I.F.; MacKenzie, D.A. Filamentous fungi for production of food additives and processing aids. In *Food Biotechnology*; Stahl, U., Donalies, U.E.B., Nevoigt, E., Eds.; Springer: Berlin/Heidelberg, Germany, 2008; pp. 99–147.
46. Yegin, S.; Fernandez-Lahore, M.; Salgado, A.J.G.; Guvenc, U.; Goksungur, Y.; Tari, C. Aspartic proteinases from *Mucor* spp. in cheese manufacturing. *Appl. Microbiol. Biotechnol.* **2011**, *89*, 949–960. [CrossRef] [PubMed]
47. Azeke, M.A.; Greiner, R.; Jany, K.D. Purification and characterization of two intracellular phytases from the tempeh fungus rhizopus oligosporus. *J. Food Biochem.* **2011**, *35*, 213–227. [CrossRef]
48. Vattem, D.A.; Shetty, K. Solid-state production of phenolic antioxidants from cranberry pomace by rhizopus oligosporus. *Food Biotechnol.* **2002**, *16*, 189–210. [CrossRef]
49. Liao, W.; Liu, Y.; Chen, S.L. Studying pellet formation of a filamentous fungus rhizopus oryzae to enhance organic acid production. *Appl. Biochem. Biotechnol.* **2007**, *137*, 689–701. [PubMed]
50. Pandey, A.; Höfer, R.; Taherzadeh, M.; Nampoothiri, M.; Larroche, C. *Industrial Biorefineries and White Biotechnology*; Elsevier: Amsterdam, The Netherlands, 2015.
51. Dhillon, G.S.; Brar, S.K.; Kaur, S.; Verma, M. Bioproduction and extraction optimization of citric acid from *Aspergillus niger* by rotating drum type solid-state bioreactor. *Ind. Crops Prod.* **2013**, *41*, 78–84. [CrossRef]
52. Okabe, M.; Lies, D.; Kanamasa, S.; Park, E.Y. Biotechnological production of itaconic acid and its biosynthesis in aspergillus terreus. *Appl. Microbiol. Biotechnol.* **2009**, *84*, 597–606. [CrossRef] [PubMed]
53. Terabayashi, Y.; Sano, M.; Yamane, N.; Marui, J.; Tamano, K.; Sagara, J.; Dohmoto, M.; Oda, K.; Ohshima, E.; Tachibana, K.; et al. Identification and characterization of genes responsible for biosynthesis of kojic acid, an industrially important compound from aspergillus oryzae. *Fungal Genet. Biol.* **2010**, *47*, 953–961. [CrossRef] [PubMed]
54. Stahl, P.D.; Klug, M.J. Characterization and differentiation of filamentous fungi based on fatty acid composition. *Appl. Environ. Microb.* **1996**, *62*, 4136–4146.
55. Rumsey, G.L.; Winfree, R.A.; Hughes, S.G. Nutritional-value of dietary nucleic-acids and purine-bases to rainbow-trout (oncorhynchus-mykiss). *Aquaculture* **1992**, *108*, 97–110. [CrossRef]
56. Kinsella, J.E.; German, B.; Shetty, J. Uricase from fish liver—Isolation and some properties. *Comp. Biochem. Phys. B* **1985**, *82*, 621–624. [CrossRef]
57. Jobling, M. Feeding and digestive functions in fishes. *J. Fish Biol.* **2009**, *75*, 756–757. [CrossRef]
58. Council, N.R. *Nutrient Requirements of Fish and Shrimp*; The National Academies Press: Washington, DC, USA, 2011; p. 392.
59. Alvim, M.C.; Peret, A.C. Food resources sustaining the fish fauna in a section of the upper sao francisco river in tres marias, mg, Brazil. *Braz. J. Biol.* **2004**, *64*, 195–202. [CrossRef] [PubMed]
60. Peretti, D.; Andrian, I.D.F. Trophic structure of fish assemblages in five permanent lagoons of the high parana river floodplain, Brazil. *Environ. Biol. Fish* **2004**, *71*, 95–103. [CrossRef]
61. Cassemiro, F.A.D.S.; Hahn, N.S.; Rangel, T.F.L.V.D. Diet and trophic ecomorphology of the silverside, odontesthes bonariensis, of the salto caxias reservoir, Rio Iguaçu, Paraná, Brazil. *Neotrop. Ichthyol.* **2018**, *1*, 127–131. [CrossRef]
62. Parzanini, C.; Parrish, C.C.; Hamel, J.-F.; Mercier, A. Trophic ecology of a deep-sea fish assemblage in the northwest Atlantic. *Mar. Biol.* **2017**, *164*, 206. [CrossRef]
63. Sanchez-Muros, M.J.; Barroso, F.G.; Manzano-Agugliaro, F. Insect meal as renewable source of food for animal feeding: A review. *J. Clean. Prod.* **2014**, *65*, 16–27. [CrossRef]
64. Moffitt, C.M.; Cajas-Cano, L. Blue growth: The 2014 fao state of world fisheries and aquaculture. *Fisheries* **2014**, *39*, 552–553. [CrossRef]
65. Kobayashi, M.; Msangi, S.; Batka, M.; Vannuccini, S.; Dey, M.M.; Anderson, J.L. Fish to 2030: The role and opportunity for aquaculture. *Aquacult. Econ. Manag.* **2015**, *19*, 282–300. [CrossRef]

66. Oliva-Teles, A.; Enes, P.; Peres, H. 8-replacing fishmeal and fish oil in industrial aquafeeds for carnivorous fish a2—Davis, d. Allen. In *Feed and Feeding Practices in Aquaculture*; Woodhead Publishing: Oxford, UK, 2015; pp. 203–233.
67. Miles, R.D.; Chapman, F.A. *The Benefits of Fish Meal in Aquaculture Diets*; IFAS Extension; University of Florida: Gainesville, FL, USA, 2006.
68. Lee, C.-S. *Dietary Nutrients, Additives and Fish Health*; John Wiley & Sons: New York, NY, USA, 2015.
69. Glasser, F.; Ferlay, A.; Chilliard, Y. Oilseed lipid supplements and fatty acid composition of cow milk: A meta-analysis. *J. Dairy Sci.* **2008**, *91*, 4687–4703. [CrossRef] [PubMed]
70. Čertík, M.; Baltészov, L.; Šajbidor, J. Lipid formation and γ-linolenic acid production by mucorales fungi grown on sunflower oil. *Lett. Appl. Microbiol.* **1997**, *25*, 101–105. [CrossRef]
71. E Fraga, M.; Maria N Santana, D.; Gatti, M.J.A.; Direito, G.; Cavaglieri, L.; Rocha Rosa, C. *Characterization of Aspergillus Species Based on Fatty acid Profiles*; Fundação Oswaldo Cruz. Instituto Oswaldo Cruz: Rio, Brazil, 2008; Volume 103, pp. 540–544.
72. Moutinho, S.; Martinez-Llorens, S.; Tomas-Vidal, A.; Jover-Cerda, M.; Oliva-Teles, A.; Peres, H. Meat and bone meal as partial replacement for fish meal in diets for gilthead seabream (*Sparus aurata*) juveniles: Growth, feed efficiency, amino acid utilization, and economic efficiency. *Aquaculture* **2017**, *468*, 271–277. [CrossRef]
73. Gatlin, D.M.; Barrows, F.T.; Brown, P.; Dabrowski, K.; Gaylord, T.G.; Hardy, R.W.; Herman, E.; Hu, G.S.; Krogdahl, A.; Nelson, R.; et al. Expanding the utilization of sustainable plant products in aquafeeds: A review. *Aquac. Res.* **2007**, *38*, 551–579. [CrossRef]
74. Naylor, R.L.; Hardy, R.W.; Bureau, D.P.; Chiu, A.; Elliott, M.; Farrell, A.P.; Forster, I.; Gatlin, D.M.; Goldburg, R.J.; Hua, K.; et al. Feeding aquaculture in an era of finite resources. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 15103–15110. [CrossRef] [PubMed]
75. Francis, G.; Makkar, H.P.S.; Becker, K. Antinutritional factors present in plant-derived alternate fish feed ingredients and their effects in fish. *Aquaculture* **2001**, *199*, 197–227. [CrossRef]
76. Berot, S.; Compoint, J.P.; Larre, C.; Malabat, C.; Gueguen, J. Large scale purification of rapeseed proteins (*Brassica napus* L.). *J. Chromatogr. B* **2005**, *818*, 35–42. [CrossRef] [PubMed]
77. Krogdahl, A.; Penn, M.; Thorsen, J.; Refstie, S.; Bakke, A.M. Important antinutrients in plant feedstuffs for aquaculture: An update on recent findings regarding responses in salmonids. *Aquac. Res.* **2010**, *41*, 333–344. [CrossRef]
78. Sawanboonchun, J.; Roy, W.J.; Robertson, D.A.; Bell, J.G. The impact of dietary supplementation with astaxanthin on egg quality in atlantic cod broodstock (*Gadus morhua* L.). *Aquaculture* **2008**, *283*, 97–101. [CrossRef]
79. Estruch, G.; Collado, M.C.; Penaranda, D.S.; Vidal, A.T.; Cerda, M.J.; Martinez, G.P.; Martinez-Llorens, S. Impact of fishmeal replacement in diets for gilthead sea bream (*Sparus aurata*) on the gastrointestinal microbiota determined by pyrosequencing the 16s rrna gene. *PLoS ONE* **2015**, *10*, e0136389. [CrossRef] [PubMed]
80. Bakke-McKellep, A.M.; Penn, M.H.; Salas, P.M.; Refstie, S.; Sperstad, S.; Landsverk, T.; Ringo, E.; Krogdahl, A. Effects of dietary soyabean meal, inulin and oxytetracycline on intestinal microbiota and epithelial cell stress, apoptosis and proliferation in the teleost atlantic salmon (*Salmo salar* L.). *Br. J. Nutr.* **2007**, *97*, 699–713. [CrossRef] [PubMed]
81. Ringo, E.; Sperstad, S.; Myklebust, R.; Refstie, S.; Krogdahl, A. Characterisation of the microbiota associated with intestine of atlantic cod (*Gadus morhua* L.)—The effect of fish meal, standard soybean meal and a bioprocessed soybean meal. *Aquaculture* **2006**, *261*, 829–841. [CrossRef]
82. Torrecillas, S.; Montero, D.; Caballero, M.J.; Pittman, K.A.; Custodio, M.; Campo, A.; Sweetman, J.; Izquierdo, M. Dietary mannan oligosaccharides: Counteracting the side effects of soybean meal oil inclusion on european sea bass (*Dicentrarchus labrax*) gut health and skin mucosa mucus production? *Front. Immunol.* **2015**, *6*, 397. [CrossRef] [PubMed]
83. Hardy, R.W.; Shearer, K.D. Effect of dietary calcium-phosphate and zinc supplementation on whole-body zinc concentration of rainbow-trout (salmo-gairdneri). *Can. J. Fish Aquat. Sci.* **1985**, *42*, 181–184. [CrossRef]
84. Ayoola, A. *Replacement of Fishmeal with Alternative Protein Source in Aquaculture Diets*; North Carolina State University: Raleigh, NC, USA, 2010.

85. Dufosse, L.; Fouillaud, M.; Caro, Y.; Mapari, S.A.S.; Sutthiwong, N. Filamentous fungi are large-scale producers of pigments and colorants for the food industry. *Curr. Opin. Biotechnol.* **2014**, *26*, 56–61. [CrossRef] [PubMed]
86. Ramos-Elorduy, J.; Pino Moreno, J.M.; Escamilla Prado, E.; Alvarado Perez, M.; Lagunez Otero, J.; Ladron de Guevara, O. Nutritional value of edible insects from the state of Oaxaca, Mexico. *J. Food Compost. Anal.* **1997**, *10*, 142–157. [CrossRef]
87. Van Leeuwen, H.J. Fungi Cultivation on Alcohol Fermentation Stillage for Useful Products and Energy Savings. US20100196994A1. 9 July 2013.
88. Barker, T.W.; Drouliscos, N.J.; Worgan, J.T. Composition and nutritional-evaluation of aspergillus-oryzae biomass grown on palm oil processing effluents. *J. Sci. Food Agric.* **1981**, *32*, 1014–1020. [CrossRef]
89. Jin, B.; van Leeuwen, H.J.; Patel, B.; Doelle, H.W.; Yu, Q. Production of fungal protein and glucoamylase by rhizopus oligosporus from starch processing wastewater. *Process Biochem.* **1999**, *34*, 59–65. [CrossRef]
90. Ferreira, J.A.; Lennartsson, P.R.; Niklasson, C.; Lundin, M.; Edebo, L.; Taherzadeh, M.J. Spent sulphite liquor for cultivation of an edible *Rhizopus* sp. *Bioresources* **2012**, *7*, 173–188.
91. Mitra, D.; Rasmussen, M.L.; Chand, P.; Chintareddy, V.R.; Yao, L.X.; Grewell, D.; Verkade, J.G.; Wang, T.; van Leeuwen, J. Value-added oil and animal feed production from corn-ethanol stillage using the oleaginous fungus mucor circinelloides. *Bioresource Technol.* **2012**, *107*, 368–375. [CrossRef] [PubMed]
92. Wikandari, R.; Millati, R.; Lennartsson, P.R.; Harmayani, E.; Taherzadeh, M.J. Isolation and characterization of zygomycetes fungi from tempe for ethanol production and biomass applications. *Appl. Biochem. Biotechnol.* **2012**, *167*, 1501–1512. [CrossRef] [PubMed]
93. Ferreira, J.A.; Lennartsson, P.R.; Taherzadeh, M.J. Production of ethanol and biomass from thin stillage using food-grade zygomycetes and ascomycetes filamentous fungi. *Energies* **2014**, *7*, 4199–4201. [CrossRef]
94. Rasmussen, M.L.; Khanal, S.K.; Pometto, A.L.; van Leeuwen, J. Water reclamation and value-added animal feed from corn-ethanol stillage by fungal processing. *Bioresource Technol.* **2014**, *151*, 284–290. [CrossRef] [PubMed]
95. Batori, V.; Ferreira, J.A.; Taherzadeh, M.J.; Lennartsson, P.R. Ethanol and protein from ethanol plant by-products using edible fungi neurospora intermedia and aspergillus oryzae. *BioMed Res. Int.* **2015**, *2015*, 176371. [CrossRef] [PubMed]
96. Yunus, F.U.N.; Nadeem, M.; Rashid, F. Single-cell protein production through microbial conversion of lignocellulosic residue (wheat bran) for animal feed. *J. Inst. Brewing* **2015**, *121*, 553–557. [CrossRef]
97. Mahboubi, A.; Ferreira, J.; Taherzadeh, M.; Lennartsson, P. Production of fungal biomass for feed, fatty acids, and glycerol by aspergillus oryzae from fat-rich dairy substrates. *Fermentation* **2017**, *3*, 48. [CrossRef]
98. Pedneault, K.; Angers, P.; Gosselin, A.; Tweddell, R.J. Fatty acid profiles of polar and neutral lipids of ten species of higher basidiomycetes indigenous to eastern Canada. *Mycol. Res.* **2008**, *112*, 1428–1434. [CrossRef] [PubMed]
99. Beopoulos, A.; Cescut, J.; Haddouche, R.; Uribelarrea, J.L.; Molina-Jouve, C.; Nicaud, J.M. Yarrowia lipolytica as a model for bio-oil production. *Prog. Lipid Res.* **2009**, *48*, 375–387. [CrossRef] [PubMed]
100. Amar, E.C.; Kiron, V.; Akutsu, T.; Satoh, S.; Watanabe, T. Resistance of rainbow trout oncorhynchus mykiss to infectious hematopoietic necrosis virus (ihnv) experimental infection following ingestion of natural and synthetic carotenoids. *Aquaculture* **2012**, *330*, 148–155. [CrossRef]
101. Kesarcodi-Watson, A.; Kaspar, H.; Lategan, M.J.; Gibson, L. Probiotics in aquaculture: The need, principles and mechanisms of action and screening processes. *Aquaculture* **2008**, *274*, 1–14. [CrossRef]
102. Ringø, E.; Olsen, R.; González Vecino, J.; Wadsworth, S. Use of immunostimulants and nucleotides in aquaculture: A review. *J. Mar. Sci. Res. Dev.* **2011**, *2*, 104. [CrossRef]
103. Staykov, Y.; Spring, P.; Denev, S.; Sweetman, J. Effect of a mannan oligosaccharide on the growth performance and immune status of rainbow trout (*Oncorhynchus mykiss*). *Aquacult. Int.* **2007**, *15*, 153–161. [CrossRef]
104. Gopalakannan, A.; Arul, V. Immunomodulatory effects of dietary intake of chitin, chitosan and levamisole on the immune system of cyprinus carpio and control of aeromonas hydrophila infection in ponds. *Aquaculture* **2006**, *255*, 179–187. [CrossRef]
105. Ai, Q.H.; Xu, H.G.; Mai, K.S.; Xu, W.; Wang, J.; Zhang, W.B. Effects of dietary supplementation of bacillus subtilis and fructooligosaccharide on growth performance, survival, non-specific immune response and disease resistance of juvenile large yellow croaker, larimichthys crocea. *Aquaculture* **2011**, *317*, 155–161. [CrossRef]

106. Awad, E.; Austin, B. Use of lupin, lupinus perennis, mango, mangifera indica, and stinging nettle, urtica dioica, as feed additives to prevent aeromonas hydrophila infection in rainbow trout, oncorhynchus mykiss (walbaum). *J. Fish Dis.* **2010**, *33*, 413–420. [CrossRef] [PubMed]
107. Dalmo, R.A.; Bogwald, J. Beta-glucans as conductors of immune symphonies. *Fish Shellfish Immunol.* **2008**, *25*, 384–396. [CrossRef] [PubMed]
108. Holdt, S.L.; Kraan, S. Bioactive compounds in seaweed: Functional food applications and legislation. *J. Appl. Phycol.* **2011**, *23*, 543–597. [CrossRef]
109. Jung-Schroers, V.; Adamek, M.; Jung, A.; Harris, S.; Doza, O.S.; Baumer, A.; Steinhagen, D. Feeding of beta-1,3/1,6-glucan increases the diversity of the intestinal microflora of carp (*Cyprinus carpio*). *Aquacult. Nutr.* **2016**, *22*, 1026–1039. [CrossRef]
110. Peng, M.; Xu, W.; Ai, Q.H.; Mai, K.S.; Liufu, Z.G.; Zhang, K.K. Effects of nucleotide supplementation on growth, immune responses and intestinal morphology in juvenile turbot fed diets with graded levels of soybean meal (*Scophthalmus maximus* L.). *Aquaculture* **2013**, *392*, 51–58. [CrossRef]
111. Nimrichter, L.; Rodrigues, M.L.; Rodrigues, E.G.; Travassos, L.R. The multitude of targets for the immune system and drug therapy in the fungal cell wall. *Microbes Infect.* **2005**, *7*, 789–798. [CrossRef] [PubMed]
112. Nguyen, T.H.; Fleet, G.H.; Rogers, P.L. Composition of the cell walls of several yeast species. *Appl. Microbiol. Biotechnol.* **1998**, *50*, 206–212. [CrossRef] [PubMed]
113. Free, S.J. Fungal cell wall organization and biosynthesis. *Adv. Genet.* **2013**, *81*, 33–82. [PubMed]
114. Peter Martin, G.; Vandamme Erick, J.; De Baets, S.; Steinbüchel, A. Chitin and Chitosan in Fungi. Available online: https://onlinelibrary.wiley.com/doi/abs/10.1002/3527600035.bpol6005 (accessed on 14 September 2018).
115. Whyte, S.K. The innate immune response of finfish—A review of current knowledge. *Fish Shellfish Immunol.* **2007**, *23*, 1127–1151. [CrossRef] [PubMed]
116. Ringo, E.; Olsen, R.E.; Gifstad, T.O.; Dalmo, R.A.; Amlund, H.; Hemre, G.I.; Bakke, A.M. Prebiotics in aquaculture: A review. *Aquacult. Nutr.* **2010**, *16*, 117–136. [CrossRef]
117. Bagni, M.; Romano, N.; Finoia, M.G.; Abelli, L.; Scapigliati, G.; Tiscar, P.G.; Sarti, M.; Marino, G. Short- and long-term effects of a dietary yeast beta-glucan (macrogard) and alginic acid (ergosan) preparation on immune response in sea bass (*Dicentrarchus labrax*). *Fish Shellfish Immunol.* **2005**, *18*, 311–325. [CrossRef] [PubMed]
118. El-Boshy, M.E.; El-Ashram, A.M.; Abdelhamid, F.M.; Gadalla, H.A. Immunomodulatory effect of dietary saccharomyces cerevisiae, beta-glucan and laminaran in mercuric chloride treated nile tilapia (*Oreochromis niloticus*) and experimentally infected with aeromonas hydrophila. *Fish Shellfish Immunol.* **2010**, *28*, 802–808. [CrossRef] [PubMed]
119. Harikrishnan, R.; Kim, J.S.; Balasundaram, C.; Heo, M.S. Dietary supplementation with chitin and chitosan on haematology and innate immune response in epinephelus bruneus against philasterides dicentrarchi. *Exp. Parasitol.* **2012**, *131*, 116–124. [CrossRef] [PubMed]
120. Yoo, G.; Lee, S.; Kim, Y.C.; Okorie, O.E.; Park, G.J.; Han, Y.O.; Choi, S.M.; Kang, J.C.; Sun, M.H.; Bai, S.C. Effects of dietary beta-1,3 glucan and feed stimulants in juvenile olive flounder, paralichthys olivaceus. *J. World Aquacult. Soc.* **2007**, *38*, 138–145. [CrossRef]
121. Mari, L.S.S.; Jagruthi, C.; Anbazahan, S.M.; Yogeshwari, G.; Thirumurugan, R.; Arockiaraj, J.; Mariappan, P.; Balasundaram, C.; Harikrishnan, R. Protective effect of chitin and chitosan enriched diets on immunity and disease resistance in cirrhina mrigala against aphanomyces invadans. *Fish Shellfish Immunol.* **2014**, *39*, 378–385. [CrossRef] [PubMed]
122. Steglich, W. Biologically-active compounds from higher fungi. *Pure Appl. Chem.* **1981**, *53*, 1233–1240. [CrossRef]
123. Velisek, J.; Cejpek, K. Pigments of higher fungi: A review. *Czech. J. Food Sci.* **2011**, *29*, 87–102. [CrossRef]
124. Velmurugan, P.; Kamala-Kannan, S.; Balachandar, V.; Lakshmanaperumalsamy, P.; Chae, J.C.; Oh, B.T. Natural pigment extraction from five filamentous fungi for industrial applications and dyeing of leather. *Carbohyd. Polym.* **2010**, *79*, 262–268. [CrossRef]
125. Nigam, P.S.; Luke, J.S. Food additives: Production of microbial pigments and their antioxidant properties. *Curr. Opin. Food Sci.* **2016**, *7*, 93–100. [CrossRef]

126. Torrissen, O.J.; Hardy, R.W.; Shearer, K.D.; Scott, T.M.; Stone, F.E. Effects of dietary canthaxanthin level and lipid-level on apparent digestibility coefficients for canthaxanthin in rainbow-trout (oncorhynchus-mykiss). *Aquaculture* **1990**, *88*, 351–362. [CrossRef]
127. Storebakken, T.; Goswami, U.C. Plasma carotenoid concentration indicates the availability of dietary astaxanthin for atlantic salmon, salmo salar. *Aquaculture* **1996**, *146*, 147–153. [CrossRef]
128. Wang, Y.J.; Chien, Y.H.; Pan, C.H. Effects of dietary supplementation of carotenoids on survival, growth, pigmentation, and antioxidant capacity of characins, hyphessobrycon callistus. *Aquaculture* **2006**, *261*, 641–648. [CrossRef]
129. Amar, E.C.; Kiron, V.; Satoh, S.; Watanabe, T. Enhancement of innate immunity in rainbow trout (oncorhynchus mykiss walbaum) associated with dietary intake of carotenoids from natural products. *Fish Shellfish Immunol.* **2004**, *16*, 527–537. [CrossRef] [PubMed]
130. Tachibana, K.; Yagi, M.; Hara, K.; Mishima, T.; Tsuchimoto, M. Effects of feeding of β-carotene-supplemented rotifers on survival and lymphocyte proliferation reaction of fish larvae (*Japanese parrotfish* (*Oplegnathus fasciatus*) and spotted parrotfish (*Oplegnathus punctatus*)): Preliminary trials. *Hydrobiologia* **1997**, *358*, 313–316. [CrossRef]
131. Bendich, A.; Olson, J.A. Biological actions of carotenoids. *FASEB J.* **1989**, *3*, 1927–1932. [CrossRef] [PubMed]
132. Hill, G.E.; Johnson, J.D. The vitamin a-redox hypothesis: A biochemical basis for honest signaling via carotenoid pigmentation. *Am. Nat.* **2012**, *180*, E127–E150. [CrossRef] [PubMed]
133. McGraw, K.J.; Ardia, D.R. Carotenoids, immunocompetence, and the information content of sexual colors: An experimental test. *Am. Nat.* **2003**, *162*, 704–712. [CrossRef] [PubMed]
134. Von Schantz, T.; Bensch, S.; Grahn, M.; Hasselquist, D.; Wittzell, H. Good genes, oxidative stress and condition-dependent sexual signals. *Proc. R. Soc. B Biol. Sci.* **1999**, *266*, 1–12. [CrossRef] [PubMed]
135. Maan, M.E.; Sefc, K.M. Colour variation in cichlid fish: Developmental mechanisms, selective pressures and evolutionary consequences. *Semin. Cell Dev. Biol.* **2013**, *24*, 516–528. [CrossRef] [PubMed]
136. Baerends, G.P.; Wanders, J.B.W.; Vodegel, R. The relationship between marking patterns and motivational state in the prespawning behavior of the cichlid fish chromidotilapia guentheri (sauvage). *Neth. J. Zool.* **1986**, *36*, 88–116. [CrossRef]
137. Kalinowski, C.T.; Robaina, L.E.; Fernandez-Palacios, H.; Schuchardt, D.; Izquierdo, M.S. Effect of different carotenoid sources and their dietary levels on red porgy (*Pagrus pagrus*) growth and skin colour. *Aquaculture* **2005**, *244*, 223–231. [CrossRef]
138. Teles Aires, O.; Lupatsch, I.; Nengas, I. Nutrition and Feeding of Sparidae. Available online: https://cronfa.swan.ac.uk/Record/cronfa8250 (accessed on 14 September 2018).
139. Barja, G. Free radicals and aging. *Trends Neurosci.* **2004**, *27*, 595–600. [CrossRef] [PubMed]
140. Miller, D.M.; Buettner, G.R.; Aust, S.D. Transition-metals as catalysts of autoxidation reactions. *Free Radic. Biol. Med.* **1990**, *8*, 95–108. [CrossRef]
141. Valko, M.; Leibfritz, D.; Moncol, J.; Cronin, M.T.D.; Mazur, M.; Telser, J. Free radicals and antioxidants in normal physiological functions and human disease. *Int. J. Biochem. Cell Biol.* **2007**, *39*, 44–84. [CrossRef] [PubMed]
142. Schuemann, J.; Hertweck, C. Biosynthesis of fungal polyketides. *Mycota* **2009**, *15*, 331–351.
143. Tian, C.C.; Zha, X.Q.; Pan, L.H.; Luo, J.P. Structural characterization and antioxidant activity of a low-molecular polysaccharide from dendrobium huoshanense. *Fitoterapia* **2013**, *91*, 247–255. [CrossRef] [PubMed]
144. Dhale, M.A.; Divakar, S.; Kumar, S.U.; Vijayalakshmi, G. Isolation and characterization of dihydromonacolin-mv from monascus purpureus for antioxidant properties. *Appl. Microbiol. Biotechnol.* **2007**, *73*, 1197–1202. [CrossRef] [PubMed]
145. Smith, H.A. *Production of Antimicrobials and Antioxidants from Filamentous Fungi*; National University of Ireland Maynooth: Kildare, Ireland, 2014.
146. Gopalakrishnan, K.; Van Leeuwen, H.; Brown, R. *Sustainable Bioenergy and Bioproducts: Value Added Engineering Applications 001*; Springer: Berlin, Germany, 2012; Volume 62.
147. Bennett, J.W.; Klich, M. Mycotoxins. *Clin. Microbiol. Rev.* **2003**, *16*, 497–516. [CrossRef] [PubMed]
148. Ramaiah, N. A review on fungal diseases of algae, marine fishes, shrimps and corals. *Indian J. Mar. Sci.* **2006**, *35*, 380–387.

149. Tisma, M.; Zelic, B.; Vasic-Racki, D. White-rot fungi in phenols, dyes and other xenobiotics treatment—A brief review. *Croat. J. Food Sci. Technol.* **2010**, *2*, 34–47.
150. Justino, C.I.; Duarte, K.; Loureiro, F.; Pereira, R.; Antunes, S.C.; Marques, S.M.; Goncalves, F.; Rocha-Santos, T.A.P.; Freitas, A.C. Toxicity and organic content characterization of olive oil mill wastewater undergoing a sequential treatment with fungi and photo-fenton oxidation. *J. Hazard. Mater.* **2009**, *172*, 1560–1572. [CrossRef] [PubMed]
151. Quintero, J.C.; Lu-Chau, T.A.; Moreira, M.T.; Feijoo, G.; Lema, J.M. Bioremediation of hch present in soil by the white-rot fungus bjerkandera adusta in a slurry batch bioreactor. *Int. Biodeter. Biodegr.* **2007**, *60*, 319–326. [CrossRef]
152. Faraco, V.; Pezzella, C.; Miele, A.; Giardina, P.; Sannia, G. Bio-remediation of colored industrial wastewaters by the white-rot fungi *Phanerochaete chrysosporium* and *Pleurotus ostreatus* and their enzymes. *Biodegradation* **2009**, *20*, 209–220. [CrossRef] [PubMed]
153. Sankaran, S.; Khanal, S.K.; Jasti, N.; Jin, B.; Pometto, A.L.; Van Leeuwen, J. Use of filamentous fungi for wastewater treatment and production of high value fungal byproducts: A review. *Crit. Rev. Environ. Sci. Technol.* **2010**, *40*, 400–449. [CrossRef]
154. Kapoor, A.; Viraraghavan, T.; Cullimore, D.R. Removal of heavy metals using the fungus *Aspergillus niger*. *Bioresource Technol.* **1999**, *70*, 95–104. [CrossRef]
155. Delgado, A.; Anselmo, A.M.; Novais, J.M. Heavy metal biosorption by dried powdered mycelium of fusarium flocciferum. *Water Environ. Res.* **1998**, *70*, 370–375. [CrossRef]