Original article

Fish industry waste: treatments, environmental impacts, current and potential uses

Ioannis S. Arvanitoyannis[1]* & Aikaterini Kassaveti[2]

1 Department of Agriculture Ichthyology and Aquatic Environment, School of Agricultural Sciences, University of Thessaly, Fytokou Street, Nea Ionia Magnesias, Volos 38446, Hellas (Greece)

2 Department of Agriculture Crop Production and Agricultural Environment, School of Agricultural Sciences, University of Thessaly, Fytokou Street, Nea Ionia Magnesias, Volos 38446, Hellas (Greece)

(Received 24 July 2006; Accepted in revised form 7 November 2006)

Summary Fish waste management has been one of the problems having the greatest impact on the environment. Fish farming detrimental effects on the marine environment in particular have become an issue of public concern. In European Union, numerous Directives, Decisions and Regulations were voted in an attempt to minimise the environmental impact of fisheries within the frame of Integrated Coastal Management. Treated fish waste has found many applications among which the most important are animal feed, biodiesel/biogas, dietic products (chitosan), natural pigments (after extraction), food-packaging applications (chitosan), cosmetics (collagen), enzyme isolation, Cr immobilisation, soil fertiliser and moisture maintenance in foods (hydrolysates). In this review, an update of both environmental impact (inputs and outputs) and treated fish waste uses is provided by means of six comprehensive tables and seven figures.

Keywords Animal feed, biogas, environmental impact, fish waste uses, input and output of fish processes.

Introduction

Marine aquaculture involves a variety of species, rearing techniques and husbandry methods. Extensive marine aquaculture involves the farming of finfish or shellfish in a 'natural' habitat with no supplementary food added and with minimum impact on the environment. Conversely, the intensive farming of marine finfish, commonly practised in cages or ponds, involves the supply of high-quality artificial feeds and medication with consequent impacts on the environment, mainly because of the release of organic and inorganic nutrients and the release of chemicals used for medication. These impacts tend to be the most severe in areas with poor water exchange [Midlen & Redding, 1998; Oceanographic Applications to Eutrophication in Regions of Restricted Exchange (OAERRE), 2001]. Fish farm waste affects not only the area surrounding and directly affected by the effluent, but can also alter a wider coastal zone at different ecosystem levels, thus reducing the biomass, density and diversity of the benthos, plankton and nekton, and modifying natural food webs (Gowen, 1991; Pillay, 1991).

*Correspondent: Fax: +30 2421093137;
e-mail: parmenion@uth.gr

The development of aquaculture has caused great concern over the management and protection of coastal environments. Aquaculture activities can have a number of negative effects on marine ecosystems. The biological changes linked to marine fish farming have been reported extensively because of the evident generation of high pollution loadings (Ackefors, 1986; Iwama, 1991; Wu, 1995). Fish farming detrimental effects on the marine environment have become an issue of public interest. Release of organic wastes might determine changes in the community structure and biodiversity of the benthic assemblages (Tsutsumi *et al.*, 1991; Wu *et al.*, 1994; Vezzulli *et al.*, 2002, 2006). Any serious effort to protect the marine environment requires the support and cooperation of fishermen and shellfishermen. While environmentalists and the scientific community may, from time to time, work actively towards protecting the marine resources, limitations on their funds and competition for their attention from other pressing environmental issues hinder their efforts (Greenbaum, 1983).

The environmental impacts of marine aquaculture within the European Union (EU) are regulated and managed by a variety of European Commission (EC) Directives and International Conventions. There are currently eight EC Directives (Hazardous Substances

doi:10.1111/j.1365-2621.2006.01513.x

Directive, Quality of Shellfish Growing Waters Directive, Shellfish Directive, Environmental Impact Assessment Directive, Strategic Environmental Assessment Directive, Species and Habitats Directive, Wild Birds Directive and Water Framework Directive), which relate directly to the management of the environmental impacts of aquaculture, plus Directives affecting the marketing of medicinal veterinary products, and Resolutions, Decisions and Communications pertaining to Integrated Coastal Zone Management. There are also more than 50 other EC Directives, Decisions and Regulations, which have an indirect effect on the monitoring and regulation of marine aquaculture (Read *et al*., 2001).

Aquaculture has grown substantially in a number of EU countries over recent years, and it is essentially an economic development within small- and medium-sized enterprises in remote areas where alternative employment is rather limited. This has been particularly evident in marine aquaculture [Atlantic salmon in Scotland, Norway and Ireland, sea bass and sea bream (*Sparus aurata*) in the Mediterranean and mussel (*Mytilus edulis*) farming by line or raft in Ireland, Spain and France]. This overall trend was enhanced because of a general decline in catchable wild fish stocks and an increase in public demand for finfish and shellfish resources (Fernandes *et al*., 2000).

While capture fisheries fall short of world demand, annual consumption of seafood has been rising, doubling in three decades (FAO, 2000). Obviously, just as man no longer depends on hunting, he can no longer depend solely on fishing. Even today, aquaculture provides over a quarter of the world's seafood supply, a figure the FAO expects will approach 50% by the year 2030 (Tidwell & Allen, 2001).

Global production of fish and shrimp has been in a steadily increasing trend over the last decade and this trend is expected to continue. Of the estimated 131 million tonnes of fish produced in 2000 in the world, nearly 74% (97 million tonnes) was used for direct human consumption. The remainder (about 26%) was utilised for various non-food products, mostly for reduction to meal and oil. As a highly perishable commodity, fish has a significant requirement for processing. In 2000, more than 60% of total world fisheries production underwent some form of processing (FAO, 2002).

An important waste reduction strategy for the industry is the recovery of marketable by-products from fish wastes. Hydrolysed fish wastes can be used for fish or pig meal as well as fertiliser components (http://www.earthprint.com/unep/download/2481.pdf). The three most common methods for utilisation of aquatic waste (either from aquaculture or wild stock) are the manufacture of fishmeal/oil, the production of silage or the use of waste in the manufacture of organic fertiliser (http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/003/X9199E/X9199E00.HTM). The utilisation of by-products is an important cleaner production opportunity for the industry, as it can potentially generate additional revenue as well as reduce disposal costs for these materials. The transportation of fish residues and offal without the use of water is an important factor for the effective collection and utilisation of these by-products (http://www.earthprint.com/unep/download/2481.pdf).

The main target of this review is to summarise the current and potential uses of treated fish waste by means of informative flow diagrams and tables and the inputs and outputs (energy consumption, wastewater, solid waste) of various fish processes.

Uses of fish waste

Food industry wastes are an important environmental contamination source. Research has been carried out in order to develop methods to convert these wastes into useful products (Perea *et al*., 1993; Kristinsson & Rasco, 2000; Larsen *et al*., 2000; Guerard *et al*., 2001; Coello *et al*., 2002; Laufenberg *et al*., 2003). Probably, more than 50% of the remaining material from the total fish capture is not used as food and involves almost 32 million tonnes of waste (Kristinsson & Rasco, 2000).

Animal feed

Nowadays, the use of food wastes as animal feed is an alternative of high interest, because it stands for environmental and public benefit besides reducing the cost of animal production (Samuels *et al*., 1991; Westendorf *et al*., 1998; Myer *et al*., 1999; Westendorf, 2000). Offal from the fishing industry could be used as a feed ingredient, as it represents a valuable source of high-quality protein and energy (New, 1996; Gabrielsen & Austreng, 1998).

Kotzamanis *et al*. (2001) studied the potential utilisation of trout offal as an ingredient of gilthead bream *S. aurata* (L.) diets. Trout offal (heads, skeletons, tails and intestines) was minced, homogenised and mixed thoroughly with other dietary ingredients for pellets preparation of experimental diets [diet A (control): 410 g kg^{-1} fishmeal and 58 g kg^{-1} fish oil; diet B: fishmeal 338 g kg^{-1} and trout heads, skeletons and tails; diet C: similar to diet A, but fish oil was substituted by trout intestines]. The microbiological load of the trout offal was low (10^4 CFU g^{-1}); while the fatty acids (FA) composition indicates that it is a good lipid source, because of total n-3 highly unsaturated fatty acids and arachidonic acid 20:4n-6 levels. However, the high level of 18:2n-6 FA of trout intestine, which is not a natural constituent of sea bream lipids, is the main drawback. Differences in liver glycogen content were more pronounced than differences in dietary carbohydrate.

Increased haematocrit values with diets (such as B) prompting faster growth have been reported (Barnhart, 1969). Trout offal is an alternative, non-polluting way of using the by-products of fish industry in sea bream diets.

Fish waste (mainly heads, bones, skin, viscera and sometimes whole fish and parsley) was heated at 65, 80, 105 and 150 °C for 12 h in order to reduce the moisture content to 10–12%, which is the recommended moisture content in animal feed (NRC (National Research Council), 1998). Fish waste proved to be a great source of minerals, protein [58% dry matter (d.m.)] and fat (19% d.m.). FA (monounsaturated acids, palmitic and oleic acids) are abundant in fish waste; while the high ash content (22% d.m.) indicates high percentage of minerals in fishmeal. Toxic substances (such as As, Pb, Hg and Cd) were detected in fish waste at rather low concentrations. Waste digestibility decreased with temperature, and hence temperatures over 105 °C should not be used in the treatment to reduce the moisture and to ensure the microbiology quality. Fish waste can be used as alternative feedstuffs in swine diets to meet partially the protein requirements and serve as a substitute for common sources of protein (i.e. soybean meal and commercial fishmeal) (Esteban *et al*., 2006).

Fish silage is a liquid product resulting from the liquefaction of a whole fish or a part (Tatterson & Windsor, 1974). Liquefaction is an autolytic process carried out by enzymes already present in the fish and accelerated by an acid that induces the proper conditions for the enzymes to breakdown the tissues and limits the growth of spoilage bacteria (Gildberg, 1993). Ensilage of fish waste, although practised in some countries several years ago, is not widely used nowadays because of the high water content, which may render transportation expensive. Moreover, fish waste silage is characterised by a disagreeable odour and this may considerably limit its use in high proportion of feed formulations (Hammoumi *et al*., 1998). Fish wastes of the species *Sardina pilchardus* were chopped, mixed with 15% molasses, inoculated with 5% starter culture of *Lactobacillus plantarum*, incubated at 22 ± 2 °C for 20 days, and then stored for 20 days. The obtained product incorporated with bran and ground barley to make different formulae was compared with commercial control feed, and then fed to broilers. The results indicated a net increase in the weights of broilers fed on fish silage supplemented with barley flour and bran, with slight differences compared with each other and with the control. Moreover, pH decreased considerably (initial value 6.13–6.75) in the fermenting product and then remained constant at 4.2 and 4.5, nitrogen decreased slightly (5.3–5.7%); while non-protein nitrogen increased considerably (220–262%). Fish waste can be used as a nitrogen source and possibly as a probiotic ingredient for poultry feeding (Hammoumi *et al*., 1998).

Chitin is a structural component in crustacean exoskeletons, which contain 15–20% chitin by dry weight. The production of chitin and chitosan from food industry waste (crustacean canning) has proved environmentally attractive and economically feasible, especially when it includes the recovery of carotenoids. Considerable amounts of chitin are present in the wastes and are marketed as a fish food additive (Arvanitoyannis, 1999; Kumar, 2000). Coward-Kelly *et al*. (2006) treated shrimp head waste (*Penaeus indicus*) with lime at different temperatures (75, 100 and 125 °C) and lime/shrimp ratios [0, 0.05, 0.1, 0.2 g $Ca(OH)_2$ per gram dry shrimp] in order to determine the repeatability, the effect of temperature and the effect of lime loading on solubilizing protein in shrimp head waste. Shrimp heads were hydrolysed in less than 15 min and do not require strong treatment conditions (low temperature, low lime loading and short times). Shrimp head waste contained 20% ash, 10.3% total Kjeldahl nitrogen corresponding to 64% crude protein and chitin, 18% lipids and other compounds; whereas little amino acid degradation occurred. The protein-rich material can be used as a monogastric animal feed supplement, and the residual solid – rich in calcium carbonate and chitin material – can be used to generate chitin and chitosan. The latter can find many applications on its own or as blends either as dietic product or as edible films for food preservation purposes (Arvanitoyannis *et al*., 1997, 1998).

Biodiesel/biogas

Biodiesel fuel, acquired from the oils and fats of vegetables and animals, is a substitute for, or an additive to, diesel fuel derived from petroleum (Alcantara *et al*., 2000). However, during the early 1980s, engine tests showed that the combustion of vegetable oils caused durability problems related to incomplete combustion such as nozzle coking, engine deposits, ring sticking and crankcase lubricant contamination (Dunn & Bagby, 2000). Furthermore, the higher viscosity of vegetable oils compared with diesel fuel caused excessive carbon deposition and thickening of lubricating oil, and was largely responsible for the problems encountered in using vegetable oils as a diesel fuel especially in relative cold areas and during cold seasons (Clark *et al*., 1983).

Kato *et al*. (2004) evaluated the ozone-treated fish waste oil as a transportation diesel fuel. Fish oil, a fish – powder by – product, was pretreated by filtration, placed in a reactor with two catalysts (iron oxide and calcium phosphate monobasic) and mixed with ozone bubbling [5 g h^{-1}, 16 g m^{-3} (about 8000 ppm)] for 1 h at room temperature (primary ozone treatment). Then the sample was filtered again and treated with ozone at the same conditions for 30 min, but without the presence of catalysts (secondary ozone treatment) (Fig. 1). The oil manufactured from fish waste was

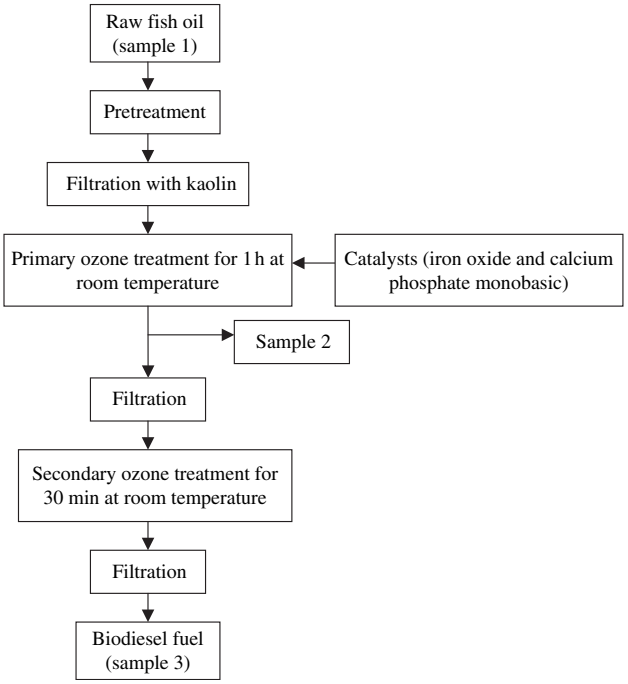

Figure 1 Ozone treatment of oils (adapted from Kato *et al*., 2004).

tested for its density, flash point, pour point, heating value, distillation test and sulphur content. The yield of the produced fuel was 95–96%, after filtration and primary and secondary treatments. The obtained oil was found to have suitable properties for use in diesel engines, such as almost identical higher heating value (10 700 kcal kg^{-1}) and density (at 15 °C, 0.87 g cm^{-3}), lower flash and pour points (37 and −16 °C, respectively) compared with commercial diesel fuel, no production of sulphur oxides, lowered or no soot, polyaromatic and carbon dioxide emissions. These properties suggested that the obtained oil had better properties than methyl-esterified vegetable oil waste and was suitable for diesel engines especially at low-temperature areas (Table 1).

There is an extensive literature on biogas production from cattle manure, piggery waste waters, by-products of aquaculture, agro-industries and urban wastes (Lo *et al*., 1986; Lo & Liao, 1986; Ng & Chin, 1987; Chapman *et al*., 1990; Montuelle *et al*., 1992; Sanchez *et al*., 1995); while no information was found on anaerobic digestion using solid wastes from fish plants. Lanari & Franci (1998) examined the potential of biogas production by fish farm effluents in a small-scale close system with partially recirculated water. The system consisted of two fish tanks with a recirculation rate of 60% and a rainbow trout daily feeding allowance of 1%, 1.5% and 2% of live weight, an upflow anaerobic digester connected with a sedimentation column and equipped with an aerobic filter run at psychrophilic conditions (24–25 °C) and with hydraulic retention time (HRT) 22–38 days, a zeolite column for final treatment of effluents, a gas flow meter and a methane analyser (Fig. 2). Biogas and methane production amounted to 49.8–144.2 L day^{-1} and 39.8–115.4 L day^{-1}, respectively. The highest biogas and methane production was reported at the highest feeding allowance, while the biogas methane content at 2% feeding allowance was higher than 80%. A remarkable reduction of volatile solids (92–97%), suspended solids (96–99%) and total ammonia nitrogen content (59–70%) in the anaerobic

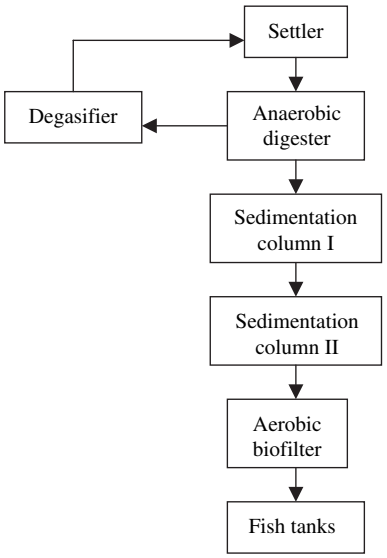

Figure 2 Experimental recirculating plant (adapted from Lanari & Franci, 1998).

Table 1 Fuels quality produces from different raw materials (adapted from Kato *et al*., 2004)

Parameters	Ozone-treated fish waste oil	Methyl-esterified vegetable oil	Diesel-derived from petroleum
Density (15 °C) (g cm^{-3})	0.87	0.88	0.84
Flash point (°C)	38	103.1	66
Pour point (°C)	−16	60	−8
HHV (kcal kg^{-1})	10700	9490	10920

Table 2 Effect of trout daily feeding allowance (1%, 1.5% and 2% of live weight) on operational data and biogas production from upflow anaerobic digester and ion-exchange column filled with zeolites (adapted from Lanari & Franci, 1998)

	Feeding allowance		
Parameters	**1%**	**1.5%**	**2%**
Upflow anaerobic digester			
Biogas production (L day^{-1})	49.8	78.8	144.2
CH_4 content in biogas (%)	>80	>80	>80
CH_4 production (L day^{-1})	39.84	63.04	115.36
pH reduction (units)	–	0.1	0.1
Total nitrogen increase (%)	157.4	26.1	23.4
TAN increase (%)	1751.4	1093.5	1533.1
Total solids decrease (%)	92	92.7	91.2
Soluble solids decrease (%)	45.5	42.6	44.7
Suspended solids decrease (%)	99.5	98.6	96.4
Volatile solids decrease (%)	97.4	96.1	93.7
Ion-exchange column filled with zeolites			
pH increase (units)	0.5	0.5	0.7
Total nitrogen decrease (%)	87.3	89.6	89.7
TAN decrease (%)	99.4	97.7	97.3
COD reduction (%)	15	35.5	44.6

digester was reported; while the zeolite ion-exchange column improved water quality of effluent produced by the digester, as the chemical oxygen demand (COD) was reduced up to 45%. The produced biogas can be used directly in a burner to produce thermal energy or, following depuration, can be employed as fuel in a cogeneration plant to produce thermal and electrical or mechanical energy (Table 2).

Most smolt hatcheries are flow-through plants with water and energy demands of up to 700 000 m^3 and 105–245 MW h per 100 000 smolts produced (Solbakken *et al*., 2005). The anaerobic treatment of sludge from salmon smolt hatchery in a continuous stirred tank reactor at mesophilic temperature (35 °C) and 55–60 days HRT was investigated by Gebauer & Eikebrokk (2005). The main components of treated sludge with 1.5–3.3% total (dry) solids were 32% nitrogen, 8.5% phosphorous, low potassium content, acceptable concentration of heavy metal apart from zinc and high levels of volatile fatty acids (VFA), which may cause phytotoxicity. The treated sludge is in liquid form and can be used as a liquid fertiliser on cultivated land and meadows; however, requirements for special means of application are needed. Furthermore, the methane content in biogas stabilised at 59.4–60.5% vol., methane yield was 0.14–0.15 L g^{-1} COD, nitrogen mineralisation increased to 70%, and 44.8–53.5% COD removed. The potential of the sludge for energy production was also exploited. The net energy production from the biogas was 43–47 MW h $year^{-1}$, and could cover 2–4% of the energy demand in flow-through hatcheries, and at least twice as much in recirculation hatcheries.

Natural pigments

Carotenoids are responsible for the colour of many important fish and shellfish products. Most expensive seafood, such as shrimp, lobster, crab, crayfish, trout, salmon, redfish, red snapper and tuna, have orange-red integument and/or flesh containing carotenoid pigments (Haard, 1992). The grading or pricing of shrimp, salmon, rockfish and snapper is directly related to the intensity of red hue (Sacton, 1986).

Shrimp waste is one of the most important natural sources of carotenoids (Shahidi *et al*., 1998). Shrimp waste, such as head and body carapace, was used for carotenoids extraction with various organic solvents [methanol, ethyl methyl ketone, isopropyl alcohol (IPA), ethyl acetate, ethanol, petroleum ether and hexane] and solvent mixtures (acetone and hexane, IPA and hexane) at various extraction conditions (percentage of hexane in the solvent mixture of IPA and hexane, ratio of solvent to waste and number of extractions) (Sachindra *et al*., 2001). The results showed that the highest carotenoid yield (43.9 μg g^{-1} waste) was recorded when the carotenoids were extracted with a mixture of IPA and hexane, followed by IPA (40.8 μg g^{-1}) and acetone (40.6 μg g^{-1}); whereas the lowest carotenoid yield was obtained with petroleum ether (12.1 μg g^{-1}) and hexane (13.1 μg g^{-1}). The optimised conditions for extraction of carotenoids from shrimp waste were 60% hexane in the solvent mixture of IPA and hexane, a solvent-to-waste ratio of five in each extraction and three extractions. The recovered carotenoids can be effectively used instead of synthetic carotenoids in aquaculture feed formulations, and the residue available after extraction may be used for the preparation of chitin/chitosan (Sachindra *et al*., 2006).

Samples of fertilised eggs, week-old fry, of *Cyprinus carpio* L. and the fish of that species, aged 1 month, 1 year and 2 years were used for carotenoid pigments recovery by Czeczuga (1979). Carotenoids were extracted by 95% acetone in a dark room. Saponification was carried out by 10% KOH in ethanol at a temperature of about 20 °C for 24 h in the dark under a nitrogen atmosphere. The obtained carotenoids were astaxanthin, β-, γ-, ε-carotene, tunaxanthin, isozeaxanthinin, phoenicoxanthin and canthaxanthin.

Food industry/cosmetics

The recovery of chemical components from seafood waste materials, which can be used in other segments of the food industry, is a promising area of research and development for the utilisation of seafood by-products. Researchers have shown that a number of useful

Table 3 Chemical composition of protein hydrolysates (g per 100 g dried matter) from different fish species (adapted from Zhang *et al*., 2002; Hossain *et al*., 2003; Khan *et al*., 2003; Ruttanapornvareesakul *et al*., 2005)

	Chemical composition			
Fish species	**Crude protein (%)**	**Crude ash (%)**	**Sugar content (%)**	**Crude lipid (%)**
Antarctic krill (*Euphausia superba*)	86.2	5.8	8.2	0.03
Kuruma prawns (*Penaeus japonicus*)	93.7	2.3	4.7	0.06
Tora velvet shrimps (*Metapenaeopsis acclivis*)	85.9	5.8	9.3	0.05
Swordtip squid (*Loligo edulis*)	87.7	7.0	3.3	0.07
Japanese flying squid (*Todarodes pacificus*)	87.7	6.1	3.4	0.26
Bigfin reef squid (*Sepioteuthis lessonania*)	87.9	6.1	3.4	0.21
Golden cuttlefish (*Sepia esculenta*)	84.3	6.9	3.6	0.12
Northern pink shrimp (*Pandalusi eous*)	89.8	4.7	4.6	0.02
Endeavour shrimp (*Metapenaeus endeavouri*)	91.5	5.2	3.0	0.01
Black tiger shrimp (*Penaeus monodon*)	91.0	5.1	3.6	0.01
	Non-protein nitrogenous compound (%)	Ash (%)	Sugar content (%)	Lipid (%)
White croker (*Agryrosomus argentatus*)	85.1	7.7	3.2	0.26
Horse mackerel (*Tachurus japonicus*)	85.8	8.7	3.0	0.23
Flying fish (*Cypselurus heterurus*)	82.3	9.2	3.6	0.18
Chub mackerel (*Scomber japonicus*)	82.7	9.4	3.1	0.17
Sardine (*Sardinops melanostictus*)	83.1	8.7	4.2	0.17

compounds can be isolated from seafood waste including enzymes, gelatin and proteins that have antimicrobial and antitumor capabilities. Chitosan, produced from shrimp and crab shell, has shown a wide range of applications from the cosmetic to pharmaceutical industries (http://ift.confex.com/ift/2001/techprogram/paper_6188.htm).

The shrimp waste consisted of 71.4% head and 28.6% shell (Meyers, 1986). This waste contains useful components such as protein, lipid and astaxanthin pigment, thus making the commercial shrimp waste an attractive material for extraction of the above-mentioned components in order to utilise them in seafood products (Mandeville *et al*., 1992). Whole shrimp heads from Northern pink shrimp (*Pandalus eous*), Endeavour shrimp (*Metapenaeus endeavouri*) and Black tiger shrimp (*Penaeus monodon*) were used for shrimp head protein hydrolysates (SHPH) isolation. The preparation of hydrolysate was carried out according to Iwamoto *et al*. (1991) with slight modifications, such as thaw of shrimp heads overnight at 4 °C, pH adjustment to 8.0 by a dilution of 1 N NaOH and pH adjustment to 6.0 using 10% HCl. The obtained SHPH stands for a great source of protein (90–91%) and amino acids (71–84%), but poor in fat (0.01–0.02%) (Table 3). Fish myofibrils preparation was conducted according to Katoh *et al*. (1977) with some modifications introduced by Nozaki *et al*. (1991). The obtained SHPH or glutamate was mixed with 5% myofibrils (dry basis) at 5 °C and pH was adjusted to 7.0. The dehydration took place at 5 °C, and when the moisture content reached 10%, further dehydration occurred. The results indicated that SHPH could suppress dehydration – induced denaturation of myofibrillar protein by hydrated water stabilisation, decreased Ca-ATPase inactivation and increased monolayer sorbed water and multilayer sorbed water of myofibrillar. Therefore, SHPH can be used as a natural food additive to suppress the denaturation of myofibrillar protein and maintain moisture in intermediate moisture foods (Ruttanapornvareesakul *et al*., 2005).

Proteases are the most important group of industrial enzymes used in the world and find several applications in the food industry (Garcia-Carreño *et al*., 1994). Proteases are mainly derived from plant, animal and microbial sources, whereas their counterparts derived from marine and other aquatic sources had not been extensively used (Haard & Simpson, 1994). Meat toughness, often attributed to two factors, myofibrillar and background toughness and toughness, is the most important factor affecting consumer assessment of beef palatability (Savell *et al*., 1987, 1989; Smith *et al*., 1987). Aoki *et al*. (2004) partially purified proteases from Northern shrimp *Pandalus borealis*, in order to tenderise beef. Shrimp heads protein was extracted, purified partially, dissolved in PBS (pH 7.4) and diluted to final concentration of 10 $\mu g\ mL^{-1}$, before added to raw beefsteaks. The mixture was incubated for 1 h at 10 °C, cooked at 70 °C, cooled and stored at 4 °C for 24 h. Shrimp proteases can be used at industrial scale in food industry as they proved to be effective for beef meat tenderisation, inactive after mild heat treatment, and active at low temperatures, thus resulting in energy savings through operation at room temperature.

Surimi is mechanically deboned, water washed, minced fish meat with cryoprotectants. Frozen storage of surimi reduces the gel-forming ability (Noguchi & Matsumoto, 1970; Kurokawa, 1979; Nozaki *et al*., 1986; Scott *et al*., 1988; MacDonald *et al*., 1992), which is attributed to the denaturation of myofibrillar proteins (Dyer, 1951; Matsumoto, 1979; Matsumoto & Noguchi, 1992). Khan *et al*. (2003) prepared fish protein hydrolysate (FPH) from fish scrap of five marine species (white croker *Agryrosomus argentatus*, horse mackerel *Tachurus japonicus*, flying fish *Cypselurus heterurus*, chub mackerel *Scomber japonicus* and sardine *Sardinops melanostictus*). Fish scraps (head, viscera, scale, skin, caudal fin and bone) were treated according to the method suggested by Iwamoto *et al*. (1991) with the following modifications: pH adjustment to 8.0 by 1 N NaOH, pH adjustment to 6.0 using DL (Hydroxybutanedioic acid)– malic acid, and pH adjustment to 7.0 by 1 N NaOH prior to ultrafiltration. The obtained FPH had the following properties: 82.3–85.8% peptides, 0.2–0.3% lipid, 7.7–9.4% ash, 3.3–4.2% sugar, sodium chloride at traces and amino acids (Glx, Arg, Lys, Ser, Ala and Leu). Lizard fish surimi was minced and mixed with 5% FPH, while moisture content was adjusted to 82.0%. Then the samples were stored at −25 °C for 180 days. FPH can be utilised as a cryoprotectant for the suppression of denaturation of muscle protein of lizard fish meat during frozen storage, because it suppressed the decrease of unfrozen water, maintained a high gel-forming ability and Ca-ATPase activity.

The extraction of milk-clotting enzymes from fish stomach mucosa for cheese manufacture would provide an inexpensive alternative to rennet substitutes for domestic use or to export to cheese-producing nations, and would become a new food-related industry. Tuna fish gastric proteases were isolated using 25% NaCl solution (w/v) at different holding times (0–3 h), prior to the enzyme activation at pH 5.0. The temperature effect on tuna fish proteases yield was studied at 4 °C and room temperature. It was found that proteases yield was higher at 4 °C than at room temperature for all holding times (0–3 h). Furthermore, tuna gastric enzyme had similar activity with standard rennet at pH 4.0–6.0; it was less sensitive to losses of activity than rennet at pH > 6.4, unstable at pH > 7.0 and lost its activity at pH > 8.0. The milk-coagulating time of tuna proteases was similar with standard rennet at incubation temperature 32 °C and pH 5.5–6.4. However, further studies are required for testing tuna protease as rennet substitute at industrial scale (Tavares *et al*., 1997).

The effect of protein hydrolysate from Antarctic krill (*Euphausia superba*) meat compared with Kuruma prawns (*Penaeus japonicus*) and Tora velvet shrimps (*Metapenaeopsis acclivis*) on the state of water and denaturation by dehydration of lizard fish (*Saurida wanieso*) myofibrils was examined by Zhang *et al*. (2002). Hydrolysate production from krill was obtained by hydrolysis using 0.1% (wet weight) endotype protease after pH adjustment to 8.0 by sodium bicarbonate, derived from *Bacillus subtilis*, at 60 °C for 2 h. Then the temperature was increased at 90 °C for 30 min and the enzymatic activity was terminated. The pH was adjusted to 6.0 by malic acid, and the sample was further hydrolysed by 0.1% (wet weight) exotype protease, derived from *Aspergillus oryzae*, and ultrafiltrated (Iwamoto *et al*., 1991). The lizard fish myofibrils were treated according to Katoh *et al*. (1977) with some modifications. The myofibrils were washed with 0.1 m KCl–20 nM Tris–maleate buffer, homogenised, filtered, lipid and salts were removed, and mixed with hydrolysates, glucose and sodium glutamate (5% dry weight per 100 g pelleted myofibrils as wet weight). The mixture was dehydrated at 5 °C and, when the moisture content reached 10%, further dehydration was conducted. The hydrolysate main components were crude protein, crude ash, sugar content, sodium chloride at traces and amino acids (Glx, Asx, Arg, Lys, Gly, Ala and Leu) (Table 3). The Antarctic krill hydrolysates had a similar effect to shrimp protein hydrolysates, stabilising the bonding of water molecules and thus leading to suppressed denaturation of myofibrils during dehydration. Hydrolysates can be utilised as suppressive additives against myofibrillar protein denaturation and as a reagent to maintain moisture in food.

Fish skin, bone and fin (by Skipjack tuna *Katsuwonus pelamis*, Japanese sea bass *Lateolabrax japonicus*, ayu *Plecoglossus altivelis*, yellow sea bream *Dentex tumifrons*, chub mackerel *S. japonicus*, bullhead shark *Hetero dontus japonicus* and horse mackerel *T. japonicus*) were examined for potential isolation of collagen. It was found that collagen recovery ranged from 36% to 54%, with the highest value recorded at ayu *P. altivelis* bone, and the lowest at Japanese sea bass *L. japonicus* fin. The denaturation temperatures were skin collagen 25.0 ± 26.5 °C, bone collagen 29.5 ± 30.0 °C and fin collagen 28.0 ± 29.1 °C, lower than porcine collagen. Collagen from fish waste can be utilised in industrial level only for supplementing the skin of land vertebrates, and as alternatives to mammalian collagen in foods, cosmetics and biomedical materials (Nagai & Suzuki, 2000).

Squid protein hydrolysate (SPH) was extracted from four squid species (Japanese flying squid *Todarodes pacificus*, bigfin reef squid *Sepioteuthis lessonania*, swordtip squid *Loligo edulis* and golden cuttlefish *Sepia esculenta*) with hydrolysis using endotype protease, derived from *B. subtilis*, at 60 °C for 2 h. The enzymatic activity was terminated by increasing the temperature to 90 °C for 30 min. After pH adjustment to 6.0, the sample was hydrolysed by exotype protease, derived from *A. oryzae*, and ultrafiltrated. The SPH composition was 84–88% protein, 6–7% ash, 3% sugar, 61–64%

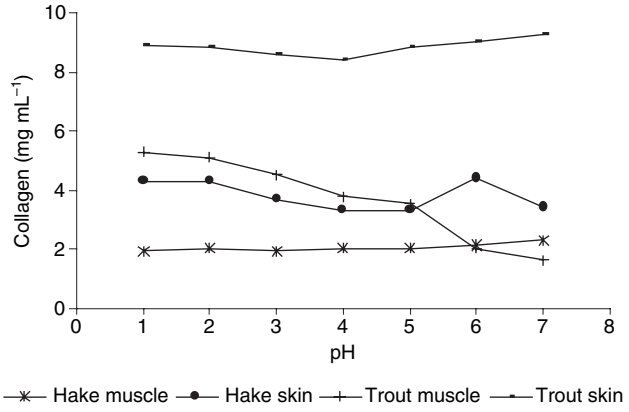

Figure 3 Concentration of various solutions of collagenous material from hake and trout muscle and skin at different pH (adapted from Montero & Borderias, 1990).

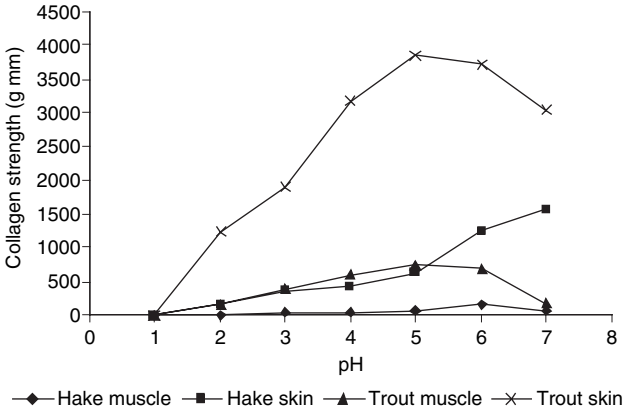

Figure 4 Gel strength of various solutions of collagenous material from hake and trout muscle and skin at different pH (adapted from Montero & Borderias, 1990).

hydrophilic amino acids, crude lipids and NaCl trace components (Table 3). The development of a functional food from squid stands for a new perspective regarding the potential use of low-cost squid meat in food processing and preservation (Hossain *et al*., 2003).

Montero & Borderias (1990) examined gel strength, which was manufactured using collagen extracted from the muscle and skin connective tissue of hake (*Merluceius merluecius* L.) and trout (*Salmo irideus* Gibb), at various pH and NaCl concentrations. Fish waste collagenous material was stirred, filtrated, stored at 3–5 °C for 24 h, diluted with solvent (1:6, w/v) at various NaC1 concentrations (0%, 1.0%, 1.5%, 2.0%, 3.0% and 6.0%). The pH levels studied in the absence of NaCI were 1–7 (adjustment with NaOH or HCl). The results revealed that trout skin had the highest collagen concentration at various pH and NaCl concentrations; whereas hake muscle had the lowest collagen concentration (Fig. 3). Furthermore, NaC1 did not affect the gel-forming capacity of muscle collagenous material; although a diminution of skin collagenous material was reported. The gel strength was greater at pH values close to 7 than in acidic media (Fig. 4). The collagen-rich product can be used as functional material in the food industry, where gelification stands for a major application.

Morimura *et al*. (2002) treated fish bone from yellowtail fish for collagen isolation. The pretreated fish waste (80% fat and 90% inorganic compounds removal from bone) was placed in a reactor with enzyme L and agitated at 200 r.p.m. for 60 min at 60 °C and pH 8.0. The mixture was then centrifuged at 8000 × ***g*** for 10 min and the precipitate weight was determined after drying at 105 °C for 24 h. The results indicated protein recovery up to 53%, high collagen degradation efficiency by enzyme L (85.5%) in comparison to enzyme K (69.2%) and other enzymes; both enzymes L and K originated from *Bacillus* species. Fat and inorganic materials from pretreatment step can be utilised for production of cooking oil and calcium apatite, respectively. The hydrolysate, a composite of oligopeptides, can be used as a food additive because of its anti-radical (antioxidant) activity and for blood pressure reduction. Finally, the solid material from enzymic hydrolysis can be used as a fertiliser (Fig. 5).

Fillets from pacific whiting *Merluccius productus* were subjected to acid-aided (pH 2 and 3, by 2 N HCl) or alkali-aided (pH 10.5, 11 and 12, by 2 N NaOH) processing methods at temperature below 5 °C for fish protein recovery. Fish proteins were then mixed with cryoprotectants (5% sucrose, 4% sorbitol and 0.3% sodium tripolyphosphate) and the pH was adjusted to approximately 7.0 using 2 N NaOH. High protein solubility was observed at pH 3 and 12, while the highest protein recovery (80%) at pH 12. The highest hydrophobicity was reported at pH 2. Total and reactive sulfhydryl concentration decreased as the pH increased from 10.5 to 12 (Fig. 6). The highest activities of cathepsin L-like enzymes were found at pH 10.5, whereas cathepsin B-like enzymes were highly activated with acid treatment (Table 4). The best textural properties (breaking force, deformation) were recorded at pH 11 and 2, whereas the worst texture at pH 10.5 (Kim *et al*., 2003) (Fig. 7).

Hake (*Merluccius hubbsi*) filleting waste was minced, mixed with water and autolysed at 60 °C. After centrifugation, the supernatant was freeze-dried to obtain solid FPH. The produced FPH contained 80% protein, and low free amino acids content appeared to have a significant nutritional value to support growth of bacteria and archaea. It can be concluded that FPH can be utilised as an alternative substrate for micro-

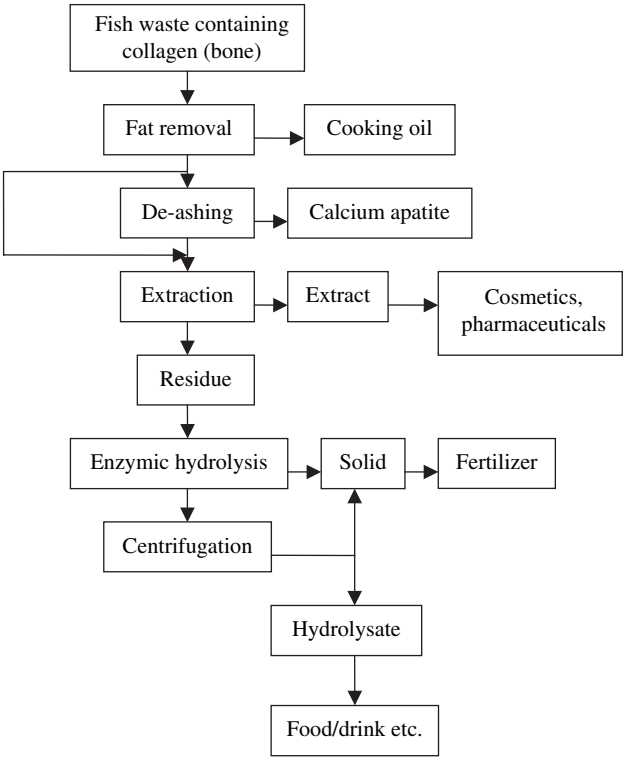

Figure 5 Flow diagram of total procedure for extraction of protein and production of peptides by enzymatic hydrolysis from fish bone (adapted from Morimura *et al.*, 2002).

organism cultural purposes (*Halobacterium salinarum*, *Escherichia coli*, *B. subtilis* and *Staphylococcus epidermidis*) (Martone *et al.*, 2005).

Waste management

To produce a stable, dry product and a high-quality fishmeal, the raw material is heated in a cooker to enable oil extraction during pressing. Pressing removes approximately 70% of the raw material mass as water and 10% as oil. The oil removed as a result of pressing is centrifuged to remove any solids. Once dried, the meal is cooled, milled and bagged or bulk loaded for transport. The majority of fish body oils are used in aquaculture feeds, except for oil derived from salmon that is exported for use in leather-tanning processes etc. Fishmeal goes to animal feed compounders for manufacture into animal feeds. Any water from the press is reused or evaporated. The Animal By-products Regulations permit the direct feeding of certain classes of animals with fish wastes. The use of wastes on maggot farms is one such possible application, although it is unlikely to be an outlet for significant volumes as there are currently no known maggot farms in Scotland. There is a potential risk for cross-examination in case maggots are reared and used as fishing bait (http://www.scotland.gov.uk/Publications/2005/03/20717/52862).

Fish bone, obtained from a natural Japanese sea bream, was heated at 600 °C for 24 h or 900 °C for 12 h, and then a removal test was conducted by adding the produced powder to nitrate solutions with aqueous chromium (Cr^{+3}) concentration 3×10^{-4} M. The mixture was stirred and soaked for 2 h, and then held for 6 days without stirring. Chromium concentration in the solution was measured by inductively coupled plasma atomic emission spectrometer. The fish bone heated at 600 °C showed better removal capacity, while raw bone and bone powder heated at 900 °C were of lower and similar activity, respectively. Raw fish bone had low crystallinity, bone sample heated at 600 °C was well-crystallised hydroxyapatite, and sample heated at 900 °C displayed the development of high crystallinity of hydroxyapatite. The results confirmed the potential utilisation of heated (600 or 900 °C) fish bone for Cr immobilisation (Ozawa *et al.*, 2003).

Astaxanthin (3,3′-dihydroxy-β,β-carotene-4 and 40-dione) is a ketocarotenoid, oxidised form of β-carotene being responsible for the pink-to-red pigmentation of the

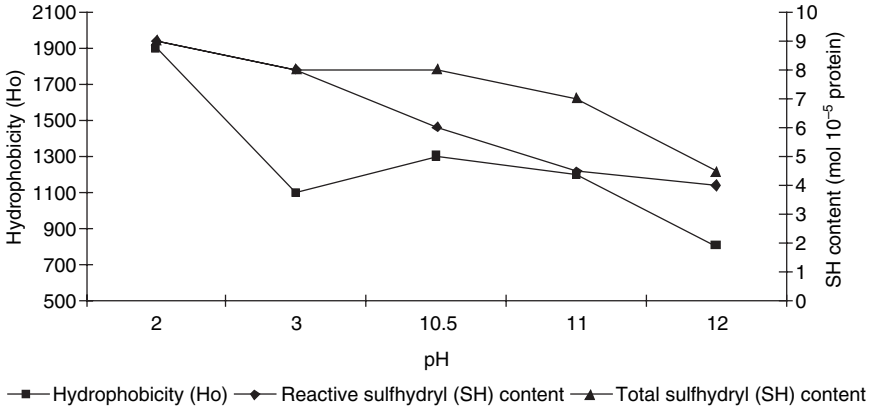

Figure 6 Hydrophobicity and total and reactive sulfhydryl (SH) content of fish proteins at various treatments (adapted from Kim *et al.*, 2003).

Table 4 Effect of pH on the protein solubility and recovery, and cathepsin B and L activity of Pacific whiting muscle (adapted from Kim *et al.*, 2003)

pH	Protein solubility (mg g^{-1})	Protein recovery (% yield)	Cathepsin B activity	Cathepsin L activity
2	90	70	1100	300
3	85	70	1300	200
5	1	–	–	–
8	20	–	–	–
9	35	–	–	–
10.5	85	60	100	1250
11	100	70	0	300
12	105	75	0	400

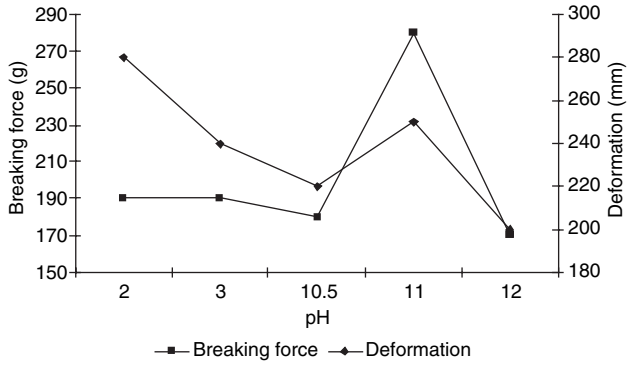

Figure 7 Textural properties of fish protein gels prepared after various treatments. Samples were treated at various pH conditions during protein recovery, and then adjusted to pH 7.0 (adapted from Kim *et al.*, 2003).

crustaceans and wild salmonids. It is widely utilised as a colouration agent for the farmed salmonids including the natural or synthetic pigment into the fish diet (Benemann, 1992; Hatlen *et al.*, 1995; Torrissen, 1995). Stepnowski *et al.* (2004) conducted sorption experiments using dry scales from redfish (*Sebastes marinus*) packed without pressure in 10 to 70-cm long PE columns supported with a reservoir filled with wastewater from shrimp factory for 5 h at room temperature. The results showed that 88–95% of astaxanthin in its esterified form was bounded to scales, and the maximum loading capacity (362 mg kg^{-1} dry weight) was found at 25–35 cm of suspension on top of scales. Furthermore, slowing down the outflow of wastewater passing through the scales of per cent of astaxanthin retention onto scales increased even to the range of 90–97%, prolonging, however, the time of the process. It can be concluded that fish scales can be utilised as a natural adsorbent for a carotenoid pigment (astaxanthin) from the seafood industry wastewater.

Miscellaneous uses

Mohan *et al.* (1993) utilised fishmeal waste as an attractant for economically important flies of agricultural crops, such as sorghum shoot fly (*Atherigona soccam* Rond.), moringa fruit fly (*Gitona* sp.) and the Indian uzifly (*Exorista bombycis* (Louis) attacking mulberry silkworm. The waste fishmeal material was dried, powdered, moistened in polyethylene bags with a piece of cotton dipped in an insecticide (Dichlorvos 76 sc, Amvac Chemical Corp. of Los Angeles, CA, USA) and placed in fields. The observations indicated that female flies were attracted and nearly 50% of them were with eggs.

Offal from the fishing industry could be used as a feed ingredient, as it represents a valuable source of high-quality protein and energy (New, 1996; Gabrielsen & Austreng, 1998). Oils from fish offal are also used extensively in the food industry as raw materials and ingredients (Jacobs *et al.*, 1997). Composting experiments of fish offal (heads, skin, viscera and skeleton) from rainbow trout and wood by-products were conducted by Laos *et al.* (1998). Fish offal was mixed with the bulking agent [a mixture of sawdust and wood shavings (1:1 by volume)] at a 3:1 ratio by weight. The blend was placed in an open structure with passively aerated method (Liao *et al.*, 1995), moisture ranging between 40% and 60% and temperature above 45 °C. Samples were taken at 20, 30, 40, 60, 80 and 100 days after composting, and dried at 60 °C. Mature compost was used as amendment at different types of soils and the mixtures were incubated aerobically at 25 °C, 20–30% soil moisture and no light during 16 weeks. Compost pH, extractable P and total nitrogen did not show a clear trend; whereas a decline in electrical conductivity (ECn), total organic carbon, NH_4–N and water-soluble carbon was reported. The VFA also decreased to non-detectable values in the case of butyric, isobutyric and propionic acids, but the acetic acid trend was erratic. Compost showed higher release of available N at a constant rate of 12% and less soil retention of bioavailable P.

Anderson *et al.* (1999) examined the possibility of benthic *Gracilaria* population grown close (1.5 km and in the waste plume) to a fish-factory waste release site and 3.5 km away (control site) during 1996. In October and November, all the *Gracilaria* at the control site died, whereas growth at the fish waste site was 8–10% per day. In November and December, control plants grew slightly faster than those from the waste site; in February the reverse occurred, and in March toJune, growth was similar at both sites. A considerable uptake of the fish-waste N by *Gracilaria* even at the control site was reported. It was thus concluded that fish waste provided an important source of nitrogen for seaweed cultivation.

Table 5 Inputs and outputs of various fish processes (adapted from http://www.agrifood-forum.net/publications/guide/f_chap4.pdf; http://www.agrifood-forum.net/publications/guide/f_chp3.pdf)

	Inputs		Outputs	
Process	**Fresh or frozen fish (kg)**	**Energy (kW h)**	**Wastewater**	**Solid waste (kg)**
White fish filleting	1000	Ice: 10–12 Freezing: 50–70 Filleting: 5	5–11 m^3: BOD 35 kg, COD_5 50 kg	Skin: 40–50 Heads: 210–250 Bones: 240–340
Oily fish filleting	1000	Ice: 10–12 Freezing: 50–70 Filleting: 2–5	5–8 m^3: BOD 50 kg, COD_5 85 kg, Nitrogen 2.5 kg N, Phosphate 0.1–0.3 kg P	400–450
Canning	1000	150–190	15 m^3: BOD 52 kg, COD_5 116 kg, Nitrogen 3 kg N, Phosphate 0.1–0.4 kg P	Heads/entrails: 250 Bones: 100–150
Fish meal and fish oil production	1000	Fuel: 49 L Electricity: 32	–	–
Frozen fish thawing	1000	–	5 m^3: COD_5 1–7 kg	–
De-icing and washing	1000	0.8–1.2	1 m^3: COD_5 0.7–4.9 kg	0–20
Granding	1000	0.1–0.3	0.3–0.4 m^3: COD_5 0.4–1.7 kg	0–20
Scaling of white fish	1000	0.1–0.3	10–15 m^3	Scales: 20–40
De-heading of white fish	1000	0.3–0.8	1 m^3: COD_5 2–4 kg	Heads and debris: 270–320
Filleting of de-headed white fish	1000	1.8	1–3 m^3: COD_5 4–12 kg	Frames and offcuts: 200–300
Filleting of un-gutted oily fish	1000	0.7–2.2	1–2 m^3: COD_5 7–15 kg	Entrails, tails, heads and frames: 400
Skinning white fish	1000	0.4–0.9	0.2–0.6 m^3: COD_5 1.7–5.0 kg	Skin: 40
Skinning oily fish	1000	0.2–0.4	0.2–0.9 m^3: COD_5 3.0–5.0 kg	Skin: 40
Trimming and cutting white fish	1000	0.3–3.0	0.1 m^3	Bones and cut-off: 240–340
Packaging of fillets	1000	5.0–7.5	–	–
Freezing and storage	1000	10.0–14.0	–	–
Unloading fish for canning	1000	3.0	2.0–5.0 m^3: COD_5 27.0–34.0 kg	–
Grading of fish	1000	0.15	0.2 m^3: COD_5 0.35–1.7 kg	0.30
Nobbing and packing in cans	1000	0.4–1.5	0.2–0.9 m^3: COD_5 7.0–15.0 kg	Heads and entrails: 150 Bones and meat: 100–150
Skinning of nobbed fish	1000	–	17.0 m^3: COD_5 3.0–5.0 kg	Skin: 55
Precooking of fish to be canned	1000	0.3–1.1	0.07–0.27 m^3	Inedible parts: 150
Draining of cans containing precooked fish	1000	0.3	0.1–0.2 m^3: COD_5 3.0–10.0 kg	–
Sauce filling	1000	–	–	Spillage of sauce and oil: varies
Can sealing	1000	5.0–6.0	–	–
Washing of cans	1000	7.0	0.04 m^3	–
Sterilisation of cans	1000	230	3.0–7.0 m^3	–
Handling and storage of fish	1000	10.0–12.0	COD_5 130.0–140.0 kg	–
Unloading of fish	1000	3.0	2.0–5.0 m^3: COD_5 27.0–34.0 kg	–
Cooking of fish	1000	90.0	–	–
Pressing the cooked fish	1000	–	750 kg water 150 kg oil	Press cake: 100 dry matter
Drying of press cake	1000	340.0	–	–
Fish oil polishing	1000	Hot water	0.05–0.1 m^3: COD_5 5 kg	–
Stick water evaporation	1000	475.0	–	Concentrated stick water: 250 Dry matter: 50

Inputs and outputs in fisheries

Fish production can generate considerable amounts of effluent, such as waste feed and faeces, medications and pesticides, which can have undesirable impacts on the environment (Gowen & Bradbury, 1987; Ackefors & Enell, 1994; Wu, 1995; Axler *et al.*, 1996; Kelly *et al.*, 1996). Fish farm effluent is often discharged directly into shallow coastal habitats determining organic and nutrient loads (mainly carbon, nitrogen and phosphorus as feed components, excreta and faeces) (Alabaster, 1982). Minimisation and enforced reduction of pollutant loads

Table 6 Fish waste; treatment method and physicochemical characteristics, substrate to be applied and final product uses

Substrate to be applied	Treatment method	Physicochemical characteristics	Final product/uses	References
Animal feed				
Trout offal (heads, skeletons, tails and intestines)	Mincing, homogenisation, pellets preparing of experimental diets	Low microbiological load (10^4 CFU g^{-1}), good lipid source because of total n-3 highly unsaturated fatty acids and arachidonic acid 20:4n-6 levels, main drawback the high level of 18:2n-6 FA of trout intestine	Dietary ingredient of gilthead bream *Sparus aurata* (L.)	Kotzamanis *et al.* (2001)
Fish waste (mainly heads, bones, skin, viscera and sometimes whole fish and parsley)	Heat treatments at 65, 80, 105 and 150 °C for 12 h for moisture content reduction to 10–12%	High source of minerals, 58% protein, 19% fat, detection of toxic substances (As, Pb, Hg and Cd) at non-problematic concentrations, decrease of waste digestibility with temperature	Feedstuff in swine diets as a protein substitute	Esteban *et al.* (2006)
Sardine fish waste	Chopped, mixed with 15% molasses, inoculated with *Lactobacillus plantarum* and incubated at 22 °C for 20 days. The obtained product was incorporated with bran and barley to make different formulas, and then fed to broilers	pH decrease in the fermenting product (then remained constant at 4.2–4.5), slight total nitrogen decrease (5.3–5.7%), non-protein nitrogen increase (220–262%)	Can be used as a nitrogen source and possibly as a probiotic ingredient for poultry feeding	Hammoumi *et al.* (1998)
Shrimp head waste	Lime treatment at different temperatures (75, 100, 125 °C) and lime/shrimp ratios (0, 0.05, 0.1, 0.2 g $Ca(OH)_2$ g^{-1} dry shrimp)	20% ash, 10.3% TKN corresponding to 64% crude protein and chitin, 18% lipids and other compounds, little amino acid degradation	Protein-rich material can be used as a monogastric animal feed supplement Residual solid – rich in calcium carbonate and chitin can – can be used to generate chitin and chitosan	Coward-Kelly *et al.* (2006)
Biodiesel/biogas				
Raw fish oil	Filtration pretreatment with or without the presence of two catalysts (iron oxide and calcium phosphate monobasic) and ozone treatment [5 g h^{-1}, 16 g m^{-3} (about 8000 ppm)] at room temperature for 1 h and 30 min, respectively	Almost identical HHV (10 700 kcal kg^{-1}) and lower flash and pour points (37 and −16 °C, respectively) compared with commercial diesel fuel, no production of sulphur oxides, lowered or no soot, polyaromatic and carbon dioxide emissions	Biodiesel fuel for transportation	Kato *et al.* (2004)
Fish-farm effluents	Small-scale close system with partially recirculated water consisted of two fish tanks with a recirculation rate of 60% and a rainbow trout daily feeding allowance 1%, 1.5% and 2% of live weight, an up-flow anaerobic digester connected with a sedimentation column and equipped with an aerobic filter run at psychrophilic conditions (24–25 °C) and with hydraulic retention time 22–38 days, a zeolite column for final treatment of effluents, a gas flow meter and a methane analyser	49.8–144.2 and 39.8–115.4 L day^{-1} bio gas and methane production, highest biogas and methane production at the highest feeding allowance, >80% biogas methane content at 2% feeding allowance, reduction of VS (92–97%), SS (96–99%), TAN content (59–70%) and COD (45%) in the anaerobic digester; improved water quality of effluent by zeolite ion-exchange column	Biogas can be used directly in a burner to produce thermal energy or, following depuration, can be employed as fuel in a cogeneration plant to obtain thermal and electrical or mechanical energy	Lanari & Franci (1998)

Table 6 (Continued)

Substrate to be applied	Treatment method	Physicochemical characteristics	Final product/uses	References
Sludge from salmon smolt hatching	Mesophilic anaerobic treatment in a continuous stirred tank reactor at 35 °C and 55–60 days hydraulic retention time	Treated sludge characteristics: 32% nitrogen, 8.5% phosphorous, low potassium content, acceptable concentration of heavy metal apart from zinc, high levels of volatile fatty acids (VFA), which may cause phytotoxicity, fertilising value of 1 tonne treated sludge 3.2–6.4 kg N and 1.2–2.4 kg P, 44.8–53.5% COD reduction Methane yields 0.14–0.15 L g^{-1} COD, net energy production from the biogas 1 million smolts 43–47 MW h $year^{-1}$	Treated sludge may cause phytotoxicity – requirements for special means of application Biogas can cover 2–4% energy demands of a flow-through hatchery	Gebauer & Eikebrokk (2005)
Natural pigments				
Shrimp waste (head and body carapace)	Extraction of shrimp waste carotenoids using different organic solvents [methanol, ethyl methyl ketone, isopropyl alcohol (IPA), ethyl acetate, ethanol, petroleum ether and hexane] and solvent mixtures (acetone and hexane, IPA and hexane) at various extraction conditions (percentage of hexane in the solvent mixture of IPA and hexane, ratio of solvent to waste and number of extractions)	Highest carotenoids yield (43.9 μg g^{-1} waste) obtained when the carotenoids were extracted with a mixture of IPA and hexane, followed by IPA (40.8 μg g^{-1}) and acetone (40.6 μg g^{-1}) Lowest carotenoid yield obtained with petroleum ether (12.1 μg g^{-1}) and hexane (13.1 μg g^{-1})	Carotenoids recovered from shrimp waste may be used instead of synthetic carotenoids in aquaculture feed formulations The residue available after carotenoids extraction may be used for the preparation of chitin/chitosan	Sachindra *et al.* (2006)
Fish fertilised eggs, week-old fry, month-old fry, 4-months-old fry, 1-year-old fry and marketable carp	Carotenoid pigments extraction by 95% acetone in a dark room, saponification by means of 10% KOH in ethanol at 20 °C for 24 h in the dark in a nitrogen atmosphere, followed by columnar and thin-layer chromatography	–	Carotenoids recovery (astaxanthin, β-, γ-, ε- carotene, tunaxanthin, isozeaxanthinin, phoenicoxanthin, canthaxanthin etc.)	Czeczuga (1979)
Food industry/cosmetics				
Fish myofibrils	Shrimp head protein hydrolysates (SHPH) were obtained according to Iwamoto *et al.* (1991) with some modifications. Fish myofibrils preparation was according to Katoh *et al.* (1977) with some modifications by Nozaki *et al.* (1991).	SHPH characteristics: suppress dehydration – induced denaturation of myofibrillar protein by hydrated water stabilisation, decrease Ca-ATPase inactivation and increase monolayer sorbed water, multilayer sorbed water of myofibrillar	Food additive to suppress the denaturation of myofibrillar protein and maintain moisture in intermediate moisture foods	Ruttanapornvareesakul *et al.* (2005)
Shrimp heads	Protease extracted from shrimp waste, purified, dissolved in PBS (pH 7.4), added to raw beefsteaks, incubated for 1 h at 10 °C, cooked at 70 °C, cooled and stored at 4 °C for 24 h, prior shear force analysis.	Overdegradation of meat proteins, efficient at low temperatures – energy minimisation, enzyme inactivation after mild heat treatment	Meet industry – beef tenderisation	Aoki *et al.* (2004)

Table 6 (Continued)

Substrate to be applied	Treatment method	Physicochemical characteristics	Final product/uses	References
Lizard fish surimi	Fish scrap (head, viscera, scale, skin, caudal fin and bone) were treated according to Iwamoto *et al*. (1991) with some modifications Minced lizard fish meat was mixed with 5.0% (dry weight/wet weight) fish protein hydrolysate (FPH), the moisture was adjusted at 82.0%, and stored at −25 °C for 180 days.	FPH components: peptide (11.5–16.3% 0 and other nitrogenous compounds (82.3–85.8%), high gel – forming ability and Ca-ATPase activity, suppression of decrease of unfrozen water content	Cryoprotectant for the suppression of denaturation of muscle protein of lizard fish meat during frozen storage	Khan *et al*. (2003)
Tuna fish waste	Tuna fish gastric proteases were isolated using 25% NaCl solution (w/v) at different holding times (0–3 h), prior to the enzyme activation at pH 5.0. The temperature influence at tuna fish proteases yield was examined at 4 °C and room temperature	Similar enzyme activity with standard rennet at pH 4.0–6.0, less sensitive to losses of activity than rennet at pH > 6.4, unstable at pH > 7.0, loss of activity at pH > 8.0, similar milk-coagulating time with standard rennet at incubation temperature 32 °C and pH 5.5–6.4	Rennet substitute – further studies are required	Tavares *et al*. (1997)
Lizard fish myofibrils	Protein hydrolysate from Antarctic krill meat was obtained according to Iwamoto *et al*. (1991). The myofibrils were washed with 0.1 m KCl–20 nM Tris–maleate buer, homogenised, filtered, lipid and salts were removed and mixed with hydrolysates, glucose and sodium glutamate (5% dry weight per 100 g pelleted myofibrils as wet weight). The mixture was dehydrated at 5 °C, and when the moisture content reached 10%, further dehydration conducted	Hydrolysate main components: crude protein, crude ash, sugar content, sodium chloride at traces and amino acids (Glx, Asx, Arg, Lys, Gly, Ala and Leu) Antarctic krill hydrolysates stabilised bonding of water molecules, and suppressed denaturation	Suppressive additives against denaturation of myofibrillar protein and as a reagent to maintain moisture in food	Zhang *et al*. (2002)
Fish skin, bone and fin	Collagen isolation	36–54% collagen recovery and denaturation temperatures of skin collagen (25.0 ± 26.5 °C), bone collagen (29.5 ± 30.0 °C) and fin collagen (28.0 ± 29.1 °C)	Use as alternatives to mammalian collagen in foods, cosmetics and biomedical materials	Nagai & Suzuki (2000)
Squid species	Hydrolysis using endotype protease (*Bacillus subtilis*), at 60 °C for 2 h, termination of enzymatic activity by increasing the temperature to 90 °C for 30 min. After pH adjustment to 6.0, the sample was hydrolysed by exotype protease (*Aspergillus oryzae*) and ultrafiltrated	SPH recovery SPH composition: 84–88% protein, 6–7% ash, 3% sugar, crude lipids and NaCl trace components	A functional food from squid as a new perspective contemplating the potential use of low-cost squid meat in food processing and preservation	Hossain *et al*. (2003)

Table 6 (Continued)

Substrate to be applied	Treatment method	Physicochemical characteristics	Final product/uses	References
Waste collagenous materials from fish (muscle and skin of hake and trout)	Stirring, filtration, storage at 3–5 °C for 24 h, dilution of collagenous material/solvent at 1:6 (w/v) (NaC1 concentrations: 0%, 1.0%, 1.5%, 2.0%, 3.0% and 6.0%). The pH levels studied in the absence of NaCl were 1–7 (adjustment with NaOH or HC1)	Trout skin had the highest collagen concentration at various pH and NaCl conditions; whereas hake muscle had the lowest collagen concentration, NaC1 did not affect the gel-forming capacity of muscle collagenous material, diminution of skin collagenous material, pH values close to neutral gel strength is greater than in acidic media	Gelifying material in the food industry	Montero & Borderias (1990)
Fish bone wastes	Pretreated (fat removal, de-ashing), treated enzymatically, agitated at 200 r.p.m. for 60 min at 60 °C and pH 8.0, centrifuged at 8000 × ***g*** for 10 min and the precipitate weight was measured after drying at 105 °C for 24 h	50% collagen recovery, high water retention capacity, high anti-radical activity, amino acid composition	Extract: used as a cosmetic material, ability to repair rough skin, lack of any odour problem and absence of harmful effects on skin Hydrolysate: used as a food additive, high twelve potential for lowering high blood pressure Fat and inorganic materials from pretreatment: production of cooking oil and calcium apatite, respectively Solid from extraction process: used as fertiliser	Morimura *et al.* (2002)
Fish fillets	Fillets were subjected to acid-aided (pH 2 and 3) or alkali-aided (pH 10.5, 11 and 12) processing methods (at <5 °C). Fish proteins were then mixed with cryoprotectants (5% sucrose, 4% sorbitol and 0.3% sodium tripolyphosphate) and the pH was adjusted to approximately 7.0 using 2N NaOH	High protein solubility at pH 3 and 12, highest protein recovery (80%) at pH 12, highest hydrophobicity at pH 2, total and reactive sulfhydryl concentration decreased as the pH increased from 10.5 to 12, highest activities of cathepsin L-like enzymes at pH 10.5, cathepsin B-like enzymes highly activated at acid treatment, best textural properties (breaking force, deformation) at pH 11 and 2, worst texture at pH 10.5	Fish proteins recovery	Kim *et al.* (2003)
Fish filleting waste	Fish wastes were minced, mixed with water, autolysed at 60 °C and centrifuged to obtain solid FPH	80% protein, low free amino acid content	Alternative substrate for microorganism cultural purposes (*Halobacterium salinarum*, *Escherichia coli*, *Bacillus subtilis* and *Staphylococcus epidermidis*)	Martone *et al.* (2005)
Waste management				
Fish bone waste	Heat treatment of raw bone at 600 °C for 24 h or 900 °C for 12 h	Better removal capacity and well-crystallised hydroxyapatite at 600°°C, raw bone showed lower activity and crystallinity, bone sample heated at 900°°C showed developed similar activity with raw bone and developed crystallinity of hydroxyapatite	Cr-immobilisation (when treated at 600 °C)	Ozawa *et al.* (2003)

Table 6 (Continued)

Substrate to be applied	Treatment method	Physicochemical characteristics	Final product/uses	References
Fish scales and wastewater	Sorption experiments using dry scales packed without pressure in 10–70 cm long PE columns supported with a reservoir filled with wastewater (5 h, at room temperature)	88–95% bond of astaxanthin to scales, maximum loading capacity (362 mg kg^{-1} dry weight) at 25–35 cm of suspension on top of scales, 90–97% astaxanthin retention onto scales by slowing down the outflow of wastewater	Natural adsorbent for a carotenoid pigment (astaxanthin) from the seafood industry wastewater	Stepnowski *et al.* (2004)
Miscellaneous use				
Fishmeal waste	The waste fishmeal material was dried, powdered, moistened in polythene bags with a piece of cotton dipped in an insecticide (Dichlorvos 76 sc) and placed in fields	Female flies were attracted and nearly 50% of them were with eggs	Attractant for economically important flies of agricultural crops [sorghum shoot fly (*Atherigona soccam* Rond.), moringa fruit fly *(Gitona* sp.) and the Indian uzifly (*Exorista bombycis* (Louis) attacking mulberry silkworm]	Mohan *et al.* (1993)
Fish offal (heads, skin, viscera and skeletons of rainbow trout)	Composting of fish offal and bulking agent [a mixture of sawdust and wood shavings (1:1 by volume)] at a 3:1 ratio by weight. The blend was placed in an open structure with passively aerated method, moisture 40–60% and temperature above 45 °C. Samples were taken at 20, 30, 40, 60, 80 and 100 days after composting, and dried at 60 °C	pH, extractable P and total nitrogen did not show a clear trend; electric conductivity, total organic carbon, NH_4 - N and water soluble carbon decline, VFA decrease to non detectable values, release of available N at a constant rate of 12% and less soil retention of bioavailable P	Soil amendment	Laos *et al.* (1998)
Fish-factory waste	Release of large quantities of nitrogen-rich fish waste	Significant source of N for cultivated seaweed (*Gracilaria gracilis*)	Nitrogen removal introduced by the fish factories	Anderson *et al.* (1999)

from point-source aquatic animal production facilities are increasingly demanded by various segments of the public and the regulatory community. The US Environmental Protection Agency is currently developing national effluent quality criteria for the US aquaculture community (MacMillan *et al*., 2003).

Water is used for treating and transporting fish, for cleaning equipment and work areas, and for fluming offal and blood. Automated processing equipment generally has permanently installed water sprays to keep equipment clean and to flush offal away. Rates of water consumption can vary considerably depending on the scale and age of the plant, the type of processing, the level of automation and the ease with which equipment can be cleaned, as well as operator practices (http://www.earthprint.com/unep/download/2481.pdf).

In fisheries, energy is used for operating machinery, producing ice, heating, cooling and drying. Apart from depleting fossil fuel resources, the consumption of energy also produces air pollution and greenhouse gas emissions, closely linked to global warming. Production of fishmeal and fish oil requires significant amounts of energy for cooking, drying and evaporation. This energy is usually generated by the combustion of fuels on site (http://www.agrifood-forum.net/publications/guide/f_chap4.pdf).

The solid wastes from fish farms falling to the seabed below fish cages are enriched in carbon, nitrogen and phosphorus relative to the natural sediments, hence fish farming may considerably alter the physicochemical nature of sediments below and adjacent to the operation, but is usually limited to the vicinity (50 m) of the cages. This increase in carbon sedimentation results in an increase in oxygen consumption by bottom-living animals. The sediments will become anoxic (i.e. contain no oxygen), if this additional oxygen demand exceeds oxygen supply, at which point there may be severe consequences for both benthic organisms and the fish farming itself (http://www.gpavlineris.com/id29_m.htm).

Although smoke and particulates may be a problem, odours are the most objectionable emissions from fish processing plants. The largest odour source in the fish by-products segment is the fishmeal driers. Odorous gases from reduction cookers consist primarily of hydrogen sulphide (H_2S) and trimethylamine [$(CH_3)_3N$], but are emitted from this stage in appreciably smaller volumes than from fishmeal driers. Some odours are also released by the canning processes. Fish cannery and fish by-product processing odours can be controlled by means of afterburners, chlorinator–scrubbers, or condensers (http://www.epa.gov/ttn/chief/ap42/ch09/final/c9s13–1.pdf). Both inputs and outputs of various fish processes are summarised in Table 5.

Conclusions

Fish waste stands for one of the continuously gaining ground waste management fields. Inputs and outputs of the various activities involved in fish processes show that the highest energy requirements occur in processes in descending order: drying of press cake, sterilisation of cans, canning and cooking. In the case of wastewater, the processes responsible for the greatest amount are skinning of nobbed fish and canning (15 and 17 m^3, respectively). Among the most prominent current uses for treated fish waste are collagen and antioxidants isolation for cosmetics, biogas/biodiesel, fertilisers, dietic applications (chitosan), food packaging (gelatine, chitosan) and enzyme isolation (proteases). On the contrary Cr complexation stands for one of the promising applications of fish bone waste to be implemented in the future. A synoptical presentation of various fish waste treatment methods, physicochemical characteristics, applied substrate and final product/uses are given in Table 6.

References

Ackefors, H. (1986). The impact on the environment by cage farming in open water. *Journal of Aquaculture in the Tropics*, **1**, 25–33.

Ackefors, H. & Enell, M. (1994). The release of nutrients and organic matter from aquaculture systems in Nordic countries. *Journal of Applied Ichthyology*, **10**, 225–241.

Alabaster, J.S. (1982). Report of the EIFAC workshop on fish farm effluents. *EIFAC Technical Paper*, 41.

Alcantara, R., Amores, J., Canoira, L., Fidaldo, E., Franco, M.J. & Navarro, A. (2000). Catalytic production of biodiesel from soy-bean oil used frying oil and tallow. *Biomass and Bioenergy*, **18**, 512–527.

Anderson, R.J., Smit, A.J. & Levitt, G.J. (1999). Upwelling and fish-factory waste as nitrogen sources for suspended cultivation of *Gracilaria gracilis* in Saldanha Bay, South Africa. *Hydrobiologia*, **398/399**, 455–462.

Aoki, H., Ahsan, Md.N., Matsuo, K., Hagiwara, T. & Watabe, S. (2004). Partial purification of proteases that are generated by processing of the Northern shrimp *Pandalus borealis* and which can tenderize beef. *International Journal of Food Science and Technology*, **39**, 471–480.

Arvanitoyannis, I. (1999). Totally-and-partially biodegradable polymer blends based on natural and synthetic macromolecules: preparation and physical properties and potential as food packaging materials. *Journal of Macromolecular Science – Reviews in Macromolecular Chemistry and Physics*, **C39**, 205–271.

Arvanitoyannis, I., Kolokuris, I., Nakayama, A., Yamamoto, N. & Aiba, S. (1997). Physicochemical studies of chitosan-poly (vinyl alcohol) blends plasticized with sorbitol and sucrose. *Carbohydrate Polymers*, **34**, 9–19.

Arvanitoyannis, I., Nakayama, A. & Aiba, S. (1998). Chitosan and gelatin based edible films: state diagrams, mechanical and permeation properties. *Carbohydrate Polymers*, **37**, 371–382.

Axler, R., Larsen, C., Tikkanen, C., McDonald, M., Yokom, S. & Aas, P. (1996). Water quality issues associated with aquaculture: a case study in mine pit lakes. *Water Environment Research*, **68**, 995–1011.

Barnhart, R.A. (1969). Effects of certain variables on hematological characteristics of rainbow trout. *Transactions of the American Fisheries Society*, **98**, 411–418.

Benemann, J.R. (1992). Microalgae aquaculture feeds. *Journal of Applied Phycology*, **4**, 233–245.
Chapman, J.M., Phillips, V.R. & Pain, B.F. (1990). Mesophilic anaerobic digestion of dairy cow slurry on farm scale: maintenance requirements and reliability. *Journal of Agricultural Engineering Research*, **47**, 277–285.
Clark, J.S., Pienaar, P.G., Wanger, L. & Schrock, W.D. (1983). Methyl ester and butyl soybean esters as a renewable fuel for diesel engines. *Journal of the American Oil Chemists Society*, **60**, 735–736.
Coello, N., Montiel, E., Concepcion, M. & Christen, P. (2002). Optimization of a culture medium containing fish silage for L-lysine production by *Corynebacterium glutamicum*. *Bioresource Technology*, **85**, 207–211.
Coward-Kelly, G., Agbogbo, F.K. & Holtzapple, M.T. (2006). Lime treatment of shrimp head waste for the generation of highly digestible animal feed. *Bioresource Technology*, **97**, 1515–1520.
Czeczuga, B. (1979). Carotenoids in fish. XXII. Changes in carotenoids in *Cyprinus carpio* L. *Hydrobiologia*, **65**, 233–240.
Dunn, O.R. & Bagby, M.O. (2000). Low-temperature phase behavior of vegetable oil co-solvent blends as alternative diesel fuel. *Journal of the American Oil Chemists Society*, **77**, 1315–1323.
Dyer, W.T. (1951). Protein denaturation in frozen and stored fish. *Food Research*, **16**, 522–527.
Esteban, M.B., Garcia, A.J., Ramos, P. & Marquez, M.C. (2006). Evaluation of fruit–vegetable and fish wastes as alternative feedstuffs in pig diets. *Waste Management*, **27**, 193–200.
FAO (2000). The state of world fisheries and aquaculture 2000. Electronic edition. Available at: http://www.fao.org/docrep/003/x8002e/x8002e00.htm.
FAO (2002). *FAO Fisheries Statistical Yearbook 2002*. Pp. 27–39. Rome: Food and Agricultural Organization of the United Nations.
Fernandes, T.F., Miller, K.L. & Read, P.A. (2000). Monitoring and regulation of marine aquaculture in Europe. *Journal of Applied Ichthyology*, **16**, 138–143.
Gabrielsen, B.O. & Austreng, E. (1998). Growth, product quality and immune status of Atlantic salmon, *Salmo salar* L. fed wet feed with alginate. *Aquaculture Research*, **29**, 397–401.
Garcia-Carreño, F.L., Hermandez-Cortes, M.P. & Haard, N.F. (1994). Enzymes with peptidase and proteinase activity from digestive systems of fresh water and a marine decapod. *Journal of Agricultural and Food Chemistry*, **42**, 1456–1461.
Gebauer, R. & Eikebrokk, B. (2005). Mesophilic anaerobic treatment of sludge from salmon smolt hatching. *Bioresource Technology*, **97**, 2389–2401.
Gildberg, A. (1993). Review: enzymic processing of marine raw materials. *Process Biochemistry*, **28**, 1–15.
Gowen, R.J. (1991). Aquaculture and the environment. In: *Aquaculture and the Environment* (edited by N. DePauw & J. Joyce). Pp. 30–38. Ghent: European Aquaculture Society Special Publications, No. 16.
Gowen, R. & Bradbury, N.B. (1987). The ecological impact of salmonid farming in coastal waters: a review. *Oceanography and Marine Biology Annual Review*, **25**, 563–575.
Greenbaum, D.S. (1983). Promoting environmental sensitivity within the fishing industry. *The Environmentalist*, **3**, 199–208.
Guerard, F., Dufosse, L., De La Broise, D. & Binet, A. (2001). Enzymatic hydrolysis of proteins from yellow fin tuna (*Thunnus albacares*) wastes using Alcalase. *Journal of Molecular Catalysis B: Enzymatic*, **11**, 1051–1059.
Haard, N.F. (1992). Biochemistry and chemistry of colour and colour change in seafood. In: *Advances in Seafood Biochemistry: Composition and Quality* (edited by G.J. Flick & R.E. Martin). 305p. Lancaster: Technomic Publishing Co. Inc.
Haard, N.F. & Simpson, B.K. (1994). Protease from aquatic organisms and their uses in the seafood industry. In: *Fisheries processing biotechnological applications* (edited by A. M. Martin). Pp. 132–154. London: Chapman & Hall.
Hammoumi, A., Faid, M., El, yachioui, M. & Amarouch, H. (1998). Characterization of fermented fish waste used in feeding trials with broilers. *Process Biochemistry*, **33**, 423–427.
Hatlen, B., Aas, G.H., Jorgensen, E.H., Storebakken, T. & Goswami, U.S. (1995). Pigmentation of 1, 2 and 3 year old Arctic charr (*Salvelinus alpinus*) fed two different dietary astaxanthin concentrations. *Aquaculture*, **138**, 303–312.
Hossain, Md. A., Ishihara, T., Hara, K., Osatomi, K., Khan, Md. A.A. & Nozaki, Y. (2003). Effect of proteolytic squid protein hydrolysate on the state of water and dehydration-induced denaturation of lizard fish myofibrillar protein. *Journal of Agricultural and Food Chemistry*, **51**, 4769–4774.
Iwama, G.K. (1991). Interactions between aquaculture and the environment. *Critical Reviews in Environmental Conservation*, **21**, 177–216.
Iwamoto, M., Fujiwara, R. & Yokoyama, M. (1991). Immunological effects of BM-2, an enzymatic digestive extract of chub mackerel. *Journal of Japanese Society for Cancer Therapeutic*, **26**, 936–947.
Jacobs, M.N., Johnston, P.A., Wyatt, C.L., Santillo, D. & French, M.C. (1997). Organochlorine pesticide and PCB residues on pharmaceutical industrial and food grade fish oils. *International Journal of Environment and Pollution*, **8**, 74–93.
Kato, S., Kunisawa, N., Kojima, T. & Murakami, S. (2004). Evaluation of ozone treated fish waste oil as a fuel for transportation. *Journal of Chemical Engineering of Japan*, **37**, 863–870.
Katoh, N., Uchiyama, H., Tsukamoto, S. & Arai, K. (1977). A biochemical study on fish myofibrillar ATPase. *Nippon Suisan Gakkaishi*, **43**, 857–867.
Kelly, L.A., Stellwagen, J. & Bergheim, A. (1996). Waste loadings from a fresh-water Atlantic Salmon farm in Scotland. *Water Research Bulletin*, **32**, 1017–1025.
Khan, M.A.A., Hossain, M.A.A., Hara, K., Osatomi, K., Tadashi, I. & Yukinori, N. (2003). Effect of enzymatic fish-scrap protein hydrolysate on gel-forming ability and denaturation of lizard fish *Saurida wanieso* surimi during frozen storage. *Fisheries Science*, **69**, 1271–1280.
Kim, Y.S., Park, J.W. & Choi, Y.J. (2003). New approaches for the effective recovery of fish proteins and their physicochemical characteristics. *Fisheries Science*, **69**, 1231–1239.
Kotzamanis, Y.P., Alexis, M.N., Andriopoulou, A., Castritsi-Cathariou, I. & Fotis, G. (2001). Utilization of waste material resulting from trout processing in gilthead bream (*Sparus aurata* L.) diets. *Aquaculture Research*, **32** (Suppl. 1), 288–295.
Kristinsson, H.G. & Rasco, B.A. (2000). Fish protein hydrolysates: production, biochemical, and functional properties. *Critical Reviews in Food Science and Nutrition*, **40**, 43–81.
Kumar, M.N. (2000). A review of chitin and chitosan applications. *Reactive and Functional Polymers*, **45**, 1–27.
Kurokawa, T. (1979). Kamaboko- forming ability of frozen and ice stored lizard fish. *Nippon Suisan Gakkaishi*, **45**, 1551–1555.
Lanari, D. & Franci, C. (1998). Biogas production from solid wastes removed from fish farm effluents. *Aquatic Living Resources*, **11**, 289–295.
Laos, F., Mazzarino, M.J., Walter, I. & Roselli, L. (1998). Composting of fish waste with wood by-products and testing compost quality as a soil amendment: experiences in the Patagonia region of Argentina. *Compost Science and Utilization*, **6**, 59–66.
Larsen, T., Thilsted, S.H., Kongsback, K. & Hanse, M. (2000). Whole small fish as a rich calcium source. *British Journal of Nutrition*, **83**, 191–196.
Laufenberg, G., Kunz, B. & Nystroem, M. (2003). Transformation of vegetable waste into value added products. *Bioresource Technology*, **87**, 167–198.
Liao, P.H., Vizcarra, A.T., Chen, A. & Lo, K.V. (1995). A comparison of different bulking agents for the composting of fish offal. *Compost Science and Utilization*, **3**, 80–86.
Lo, K.V. & Liao, P.H. (1986). Psychrophilic anaerobic digestion of screened dairy manure. *Energy in Agriculture*, **5**, 339–345.

Lo, K.V., Chen, W.Y. & Liao, P.H. (1986). Mesophilic digestion of screened dairy manure using anaerobic rotating biological contact reactor. *Biomass*, **9**, 8l–92.

MacDonald, G.A., Lelievre, J. & Wilson, D.C. (1992). Effect of frozen storage on the gel-forming properties of hoki (*Macruronus novaezelandiae*). *Journal of Food Science*, **57**, 69–71.

MacMillan, J.R., Huddleston, T., Woolley, M. & Fothergill, K. (2003). Best management practice development to minimize environmental impact from large flow-through trout farms. *Aquaculture*, **226**, 91–99.

Mandeville, S., Yaylayan, V. & Simpson, B.K. (1992). Proximate analysis, isolation and identification of amino acids and sugars from raw and cooked commercial shrimp waste. *Food Biotechnology*, **6**, 51–64.

Martone, C.B., Perez Borla, O. & Sanchez, J.J. (2005). Fishery by-product as a nutrient source for bacteria and archaea growth media. *Bioresource Technology*, **96**, 383–387.

Matsumoto, J.J. (1979). Denaturation of fish muscle proteins during frozen storage. In: *Proteins at Low Temperature* (edited by O. Fennema). Pp. 206–224. Washington, DC: American Chemical Society.

Matsumoto, J.J. & Noguchi, S. (1992). Cryostabilization of protein in surimi. In: *Surimi Technology* (edited by T.C. Lanier & C.M. Lee). Pp. 357–388. New York, NY: Marcel Dekker Inc.

Meyers, S.P. (1986). Utilization of shrimp processing waste. *Infofish Marketing Digest*, **4**, 18–19.

Midlen, A. & Redding, T. (1998). *Environmental Management for Aquaculture*. 223p. London: Chapman & Hall.

Mohan, S., Gopalan, M. & Sreenarayanan, V.V. (1993). Fish-meal waste as an attractant for economically important flies of agricultural crops. *Bioresource Technology*, **43**, 175–176.

Montero, P. & Borderias, J. (1990). Gelification of collagenous material from muscle and skin of hake (*Merluccius merluccius* L.) and trout (*Salmo irideus* Gibb) according to variation in pH and the presence of NaCI in the medium. *Zeitschrift fur Lebensmittel Untersuchung und Forschung*, **191**, 11–15.

Montuelle, B., Caillard, J. & Le Hy, J.B. (1992). A combined anaerobic-aerobic process for the co-treatment of effluents from a piggery and a cheese factory. *Journal of Agricultural Engineering Research*, **51**, 91–100.

Morimura, S., Nagata, H., Uemura, Y., Fahmi, A., Shigematsu, T. & Kida, K. (2002). Development of an effective process for utilization of collagen from livestock and fish waste. *Process Biochemistry*, **37**, 1403–1412.

Myer, R.O., Brendemuhl, J.H. & Johnson, D.D. (1999). Evaluation of dehydrated restaurant food waste products as feedstuffs for finishing pigs. *Journal of Animal Science*, **77**, 685–692.

Nagai, T. & Suzuki, N. (2000). Isolation of collagen from fish waste material – skin, bone and fin. *Food Chemistry*, **68**, 277–281.

New, M. (1996). Responsible use of aquaculture feeds. *Aquaculture Asia*, **1**, 3–15.

Ng, W.J. & Chin, K.K. (1987). Random packed anaerobic filter in piggery wastewater treatment. *Biological Wastes*, **20**, 157–166.

Noguchi, S. & Matsumoto, J.J. (1970). Studies on the control of the denaturation of the fish muscle proteins during the frozen storage – I. Preventive effect of Na-glutamate. *Nippon Suisan Gakkaishi*, **36**, 1078–1087.

Nozaki, Y., Yamamoto, T. & Tabara, Y. (1986). On board treatment of lizard fish as raw material for fish jelly products. *Nippon Suisan Gakkaishi*, **52**, 1565–1572.

Nozaki, Y., Ichikawa, H. & Tabata, Y. (1991). Effect of amino acid on the state of water and ATPase activity accompanying dehydration of fish myofibrils. *Nippon Suisan Gakkaishi*, **57**, 1531–1537.

NRC (National Research Council) (1998). *Nutrient Requirements of Swine*, 10th edn. Pp. 3–7, 45–57, 90, 115. Washington, DC: National Academy Press.

Oceanographic Applications to Eutrophication in Regions of Restricted Exchange (OAERRE) (2001). Oceanographic applications to eutrophication in regions of restricted exchange (on-line). Available at: http://www.oaerre.napier.ac.uk (accessed 01/01/02).

Ozawa, M., Satake, K. & Suzuki, R. (2003). Removal of aqueous chromium by fish bone waste originated hydroxyapatite. *Journal of Materials Science Letters*, **22**, 513–514.

Perea, A., Ugalde, U., Rodriguez, I. & Serra, J.L. (1993). Preparation and characterization of whey protein hydrolysates: application in industrial whey bioconversion processes. *Enzyme and Microbial Technology*, **15**, 418–423.

Pillay, T.V.R. (1991). *Aquaculture and the Environment*. Pp. 26–45. London: Blackwell Scientific Publications.

Read, P.A., Fernandes, T.F., Miller, K.L. et al. (Eds) (2001). The implications of directives, conventions and codes of practice on the monitoring and regulation of marine aquaculture in Europe. Proceedings of the Second MARAQUA Workshop, 114p. Institute of Marine Biology, Crete, 20–22 March 2000. Aberdeen: Scottish Executive.

Ruttanapornvareesakul, Y., Ikeda, M., Hara, K., Osako, K., Kongpun, O. & Nozaki, Y. (2005). Effect of shrimp head protein hydrolysates on the state of water and denaturation of fish myofibrils during dehydration. *Fisheries Science*, **71**, 220–228.

Sachindra, N.M., Bhaskar, N., Sakhare, P.Z., Mahendrakar, N.S. & Narasimha Rao, D. (2001). An improved process for recovery of carotenoids from crustacean waste, Indian Patent 95/DEL/2001, 31 January 2001.

Sachindra, N.M., Bhaskar, N. & Mahendrakar, N.S. (2006). Recovery of carotenoids from shrimp waste in organic solvents. *Waste Management*, **26**, 1092–1098.

Sacton, J. (1986). *The Seafood Handbook: Seafood Business*. 70p. Seattle, WA: John Wiley & Sons.

Samuels, W.A., Fontenot, J.P., Allen, V.G. & Abazinge, M.D. (1991). Seafood processing wastes ensiled with straw: utilization and intake by sheep. *Journal of Animal Science*, **69**, 4983–4992.

Sanchez, E.P., Monroy, O., Canizares, R.O., Travieso, L. & Ramos, A. (1995). A preliminary study of piggery waste treatment by an upflow sludge bed anaerobic reactor and a packed bed anaerobic reactor. *Journal of Agricultural Engineering Research*, **62**, 71–76.

Savell, J.W., Branson, R.F. & Cross, H.R. (1987). National consumer retail beef study: palatability evaluations of beef loin steaks that differed in marbling. *Journal of Food Science*, **52**, 517–519,

Savell, J.W., Cross, H.R. & Francis, J.J. et al. (1989). National consumer retail beef study: interaction of trim level, price and grade on consumer acceptance of beef steaks and roasts. *Food Quality*, **12**, 251–274.

Scott, D.N., Porter, R.W., Kudo, G., Miller, R. & Kroury, B. (1988). Effect of the freezing and frozen storage of Alaska pollack on the chemical and gel-forming properties of surimi. *Journal of Food Science*, **53**, 353–356.

Shahidi, F., Metusalach, G. & Brown, J.A. (1998). Carotenoid pigments in seafoods and aquaculture. *Critical Reviews in Food Science*, **38**, 1–67.

Smith, G.C., Savell, J.W. & Cross, H.R. (1987). Relationship of USDA quality grades to palatability of cooked beef. *Journal of Food Quality*, **10**, 269–287.

Solbakken, J., Hesjevik, J.I., Liltved, H., Johannson, R., Windmar, L. & Vogelsang, C. (2005). *Beste tilgjengelige teknikker forfiskeoppdrett i Norden*. In: TemaNord Pp. 5–139. (in Norwegian).

Stepnowski, P., Olafsson, G., Helgason, H. & Jastor, B. (2004). Recovery of astaxanthin from seafood wastewater utilizing fish scales waste. *Chemosphere*, **54**, 413–417.

Tatterson, I.N. & Windsor, M.L. (1974). Fish silage. *Journal of the Science of Food and Agriculture*, **25**, 369–379.

Tavares, J.F.P., Baptista, J.A.B. & Marcone, M.F. (1997). Milk-coagulating enzymes of tuna fish waste as a rennet substitute. *International Journal of Food Science and Nutrition*, **48**, 169–176.

Tidwell, J.H. & Allen, G.L. (2001). Fish as food: aquaculture's contribution. Ecological and economic impacts and contributions of fish farming and capture fisheries. *EMBO Reports*, **21**, 958–963.

Torrissen, O.J. (1995). Strategies for salmonid pigmentation. *Journal of Applied Ichthyology*, **11**, 276–281.
Tsutsumi, H., Kikuchi, T., Tanaka, M., Higashi, T., Imasaka, K. & Miyazaki, M. (1991). Benthic faunal succession in a cove organically polluted by fish farming. *Marine Pollution Bulletin*, **23**, 233–238.
Vezzulli, L., Chelossi, E., Riccardi, G. & Fabiano, M. (2002). Bacterial community structure and activity in fish farm sediment of the Ligurian Sea (Western Mediterranean). *Aquaculture International*, **10**, 123–141.
Vezzulli, L., Marrale, D., Moreno, P. & Fabiano, M. (2003). Organic matter and meiofauna community in longterm impacted fish-farm sediments of the Ligurian Sea (Western Mediterranean). *Chemistry Ecology*, **19**, 431–440.
Westendorf, M.L. (2000). Food waste as animal feed: an introduction. In: *Food Waste to Animal Feed* (edited by Michael L. Westendorf). Pp. 3–16, 69–90. Ames: Iowa State University Press.
Westendorf, M.L., Dong, Z.C. & Schoknecht, P.A. (1998). Recycled cafeteria food waste as a feed for swine: nutrient content digestibility, growth, and meat quality. *Journal of Animal Science*, **76**, 2976–2983.
Wu, R.S.S. (1995). The environmental impact of marine fish culture: towards a sustainable future. *Marine Pollution Bulletin*, **31**, 159–166.
Wu, R., Lam, K., MacKay, D., Lau, T. & Yam, V. (1994). Impact of marine fish farming on water quality and bottom sediment: a case study in the sub tropical environment. *Marine Environmental Research*, **38**, 115–145.
Zhang, N., Yamashita, Y. & Nozaki, Y. (2002). Effect of protein hydrolysate from Antarctic krill meat on the state of water and denaturation by dehydration of lizard fish myofibrils. *Fisheries Science*, **68**, 672–679.

Electronic sources

http://www.earthprint.com/unep/download/2481.pdf (accessed 10 April 2006).
http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/003/X9199E/X9199E00.HTM (accessed 10 April 2006).
http://www.agrifood-forum.net/publications/guide/f_chap4.pdf (accessed 25 April 2006).
http://www.gpavlineris.com/id29_m.htm (accessed 1 May 2006).
http://www.epa.gov/ttn/chief/ap42/ch09/final/c9s13–1.pdf (accessed 1 May 2006).
http://www.agrifood-forum.net/publications/guide/f_chp3.pdf (accessed 18 May 2006).
http://ift.confex.com/ift/2001/techprogram/paper_6188.htm (accessed 27 September 2006).
http://www.scotland.gov.uk/Publications/2005/03/20717/52862 (accessed 29 September 2006).

