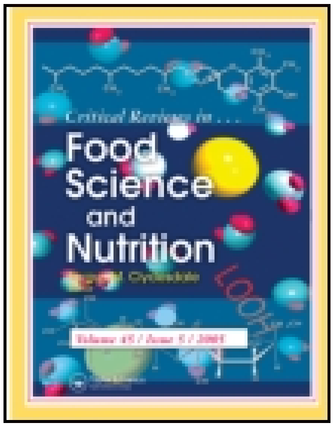

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Perspectives on the Utilization of Aquaculture Coproduct in Europe and Asia: Prospects for Value Addition and Improved Resource Efficiency

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Perspectives on the Utilization of Aquaculture Coproduct in Europe and Asia: Prospects for Value Addition and Improved Resource Efficiency

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Aquaculture has often been criticized for its environmental impacts, especially efficiencies concerning global fisheries resources for use in aquafeeds among others. However, little attention has been paid to the contribution of coproducts from aquaculture, which can vary between 40% and 70% of the production. These have often been underutilized and could be redirected to maximize the efficient use of resource inputs including reducing the burden on fisheries resources. In this review, we identify strategies to enhance the overall value of the harvested yield including noneffluent processing coproducts for three of the most important global aquaculture species, and discuss the current and prospective utilization of these resources for value addition and environmental impact reduction. The review concludes that in Europe coproducts are often underutilized because of logistical reasons such as the disconnected nature of the value chain, and perceived legislative barriers. However, in Asia, most coproducts are used, often innovatively but not to their full economic potential and sometimes with possible human health and biosecurity risks. These include possible spread of diseased material and low traceability in some circumstances. Full economic and environmental appraisal is long overdue for the current and potential strategies available for coproduct utilization.

Keywords Processing, fishmeal, omega-3 oils, regulation, halal, kosher

INTRODUCTION

Fish production from capture fisheries and aquaculture has received criticism for inefficiency of resources and environmental damage. Whereas capture fishery production has remained fairly static at around 90 million tons, aquaculture production has steadily increased from 26.7 million tons in 1996 (FAO, 2002a) to 51.7 million tons in 2006 (FAO, 2009a). Global aquaculture production is dominated by China at 62% by volume in 2009, largely for domestic markets (FAO, 2010). However, the rest of the world has seen rapid expansion, representing significant trade and income. Globally, aquaculture continues to be the fastest food growth industry, expanding at a rate roughly four times that of terrestrial livestock species combined (FAO, 2009a).

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In addition to food capture fisheries, in excess of 30 million tons of fish are caught each year for nonfood purposes, mainly for the manufacture of fishmeal and oil for use as feed and feed supplements in aquaculture, pig, and poultry production (Figure 1). Aquaculture especially has often been criticized for inefficient use of fishmeal and oil, which could perhaps be used for direct human consumption (De Silva and Turchini, 2008) and for putting pressure on supplies which can threaten ecosystems (Alder et al., 2008). However, little attention has been paid to the potential for aquaculture to produce fishmeal and oil to feed other livestock through processing of coproducts. For the purposes of this review, coproducts are defined as parts of the animal, other than the fillet, which may have some value but are often under-utilized. Byproducts are defined as those parts which cannot readily be used to add value and must be disposed of. Where mortalities may be considered as byproduct or coproduct, they will be referred to separately. In 2008, the estimated quantity of fish used in fishmeal and oil production was

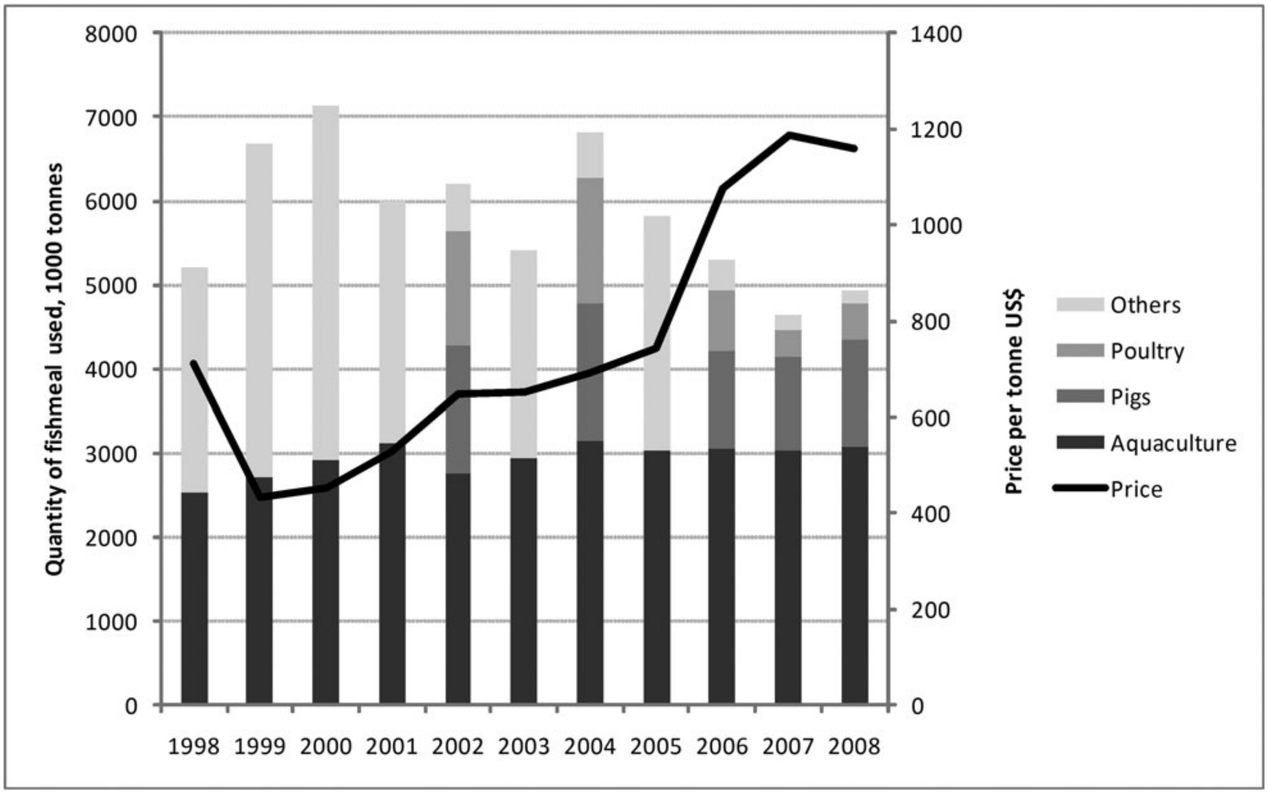

Figure 1 Trend in price and distribution of global fishmeal production for aquaculture and other use (detail where available). Source: (De Silva 2008; FAO 2002a, 2010; International Monetary Fund 2010; Seafish 2009a, 2010; Tacon and Metian 2008).

20.8 million tons, although this is significantly lower than the estimated 30 million tons used in 1994 (FAO, 2009a). Although the quantity of fishmeal used in aquaculture has remained fairly constant for about 10 years at around 3 million tons, the total supply has varied greatly, due to El Niño events for example. This has resulted in highly fluctuating prices for both fishmeal and oil and increasing pressure on the aquaculture industry, particularly that of carnivorous fish such as salmon, which still consume large quantities of fishmeal.

The reliance of aquaculture on fish oil is even greater than fishmeal, and is estimated to utilize between 80% and 90% of global supplies annually, compared to the 1970s when most was directed toward hydrogenation plants to be converted to trans-fats, used in margarines for example (Bimbo, 2007). The recent promotion of omega-3 fatty acids as health promoters has seen an upsurge in the demand for encapsulated fish oil, growing at over 4% per annum between 2003 and 2007 in the United States (Snyder, 2010), putting further pressures on prices and supplies. As many of the capture fisheries used for fishmeal and oil production are fully exploited (FAO, 2002b; Fishmeal Information Network, 2008), it is becoming increasingly important to maximize the efficiency of resource use from aquaculture and fishery products. In addition, with increasing production costs and competition, profit margins have been squeezed for many producers (Borch, 1999; Lam et al., 2009). It is therefore becoming more important to add value to the product wherever possible throughout the value chain.

While there has been some research to investigate the potential for coproducts, lack of knowledge transfer, logistical barriers, and the strict European Union (EU) Animal By-Product Regulations (European Commission, 2002, 2003) have proven prohibitive to European products and imports to the European Economic Area (EEA, the 27 EU countries plus Norway, Iceland, and Liechtenstein). Many technologies are available that enable value to be added through coproducts, and these are often used innovatively in Asia. However, there are areas where efficiency can be massively improved in Europe and Asia by employing such technologies and a full study of methodologies is long overdue. In some cases, scaling to commercial levels still remains a challenge in respects to purification, efficiency, documentation, and verification of health claims, commercial licensing, and marketability. (Raghavan and Kristinsson, 2009; Thorkelsson and Kristinsson, 2009). There has been little progress into how to integrate the technologies and ideas for the aquaculture sector and the organizational structure to facilitate their uptake in terms of cost benefit, environmental impact, and future projections. However, fish products may have particular advantages over porcine and bovine products for religious reasons, particularly in Asia, and therefore aquaculture products hold significant opportunity for value addition.

This review discusses the current and prospective technologies available, previous studies on coproduct, comparisons with current practices, and how future research and development

Table 1 Fillet yield, expected mortality, and proximate analysis of whole carcass and entire coproduct postfilleting, for farmed Atlantic salmon, striped catfish, and penaeid shrimp

Species	Fillet yield %	Mortality %	Water %	Protein %	Lipid %	Ash %	Omega-3 FA,% total
Whole animal*							
Atlantic salmon	62[1]	5[2]	65.9[3]	18.9[3]	13.7[3]	2.6[3]	39.3[4]
Striped catfish	35[5]	30[6]	76.8[7]	12.8[7]	5.6[7]	4.0[7]	—
Penaeid shrimp	50[8]	55[9]	74.9[10]	18.0[10]	1.2[10]	3.4[10]	22.9†[11]
Coproduct							
Atlantic salmon	—	—	62.1[3]	16.9[3]	19.1[3]	4.7[3]	43.6[12]
Striped catfish	—	—	73.6[13]	11.8[13]	7.9[13]	5.6[13]	—
Penaeid shrimp	—	—	69.3[14]	18.9[14]	1.2[14]	5.8[14]	19.1[14]

*Whole animal figures for striped catfish were taken from fingerlings of average weight 7.6 g. Atlantic salmon and penaeid shrimp figures from market size animals except †whole shrimp omega-3 content is for Indian white shrimp, *Fenneropenaeus indicus* at average weight 17.6 g, all others are for the black tiger shrimp, *Penaeus monodon*. Coproduct figures are extrapolated from whole fish quantities, fillet yields and quantities.

Source: 1. Ramírez, 2007; 2. SEPA, 2004; 3. Einen and Roem, 1997; 4. Stubhaug et al., 2007; 5. Le Nguyen 2007; 6. Lam et al., 2009; 7. Hung et al., 2010; 8. Benjakul et al., 2009; 9. Briggs et al., 2005; 10. Focken et al., 1998; 11. Ouraji et al., 2009; 12. Higgs et al., 2006; 13. Polak-Juszczak, 2007; 14. Sriket et al., 2007

should be directed in order to maximize efficiency and sustainability in a number of contexts.

COPRODUCT AVAILABILITY

European Economic Area

Aquaculture in the EEA is dominated by salmonid production, particularly Atlantic salmon, the majority of which is grown in Norway. Here, the combined production of salmonids was in excess of 800,000 tons in 2008 (Norwegian Directorate of Fisheries, 2009) and more than the EU27 marine finfish aquaculture production combined (Zampogna, 2009). Estimated fillet yields from farmed salmonids are about 62%, with 9%, 18%, 9%, and 2% wet weight, making up the viscera, head, backbone, and skin, respectively (Table 1) (Ramírez, 2007). The most significant coproduct streams are viscera at the point of slaughter and then the heads, bones, and often the skin after transportation to the processing plants. In some circumstances, the slaughter and processing may be combined.

Norway exports more than half of its product (Whole Fish Equivalents, WFE) to the EU as whole/eviscerated fish, mostly for further processing (Global Agriculture Information Network, 2007) and further exportation within the EU (Figure 2). Despite this, according to RUBIN (2009) there was at least 60,000 tons of salmon coproduct available in Norway in 2008. Recently, much of the processing of eviscerated Norwegian salmon has moved from Denmark and Germany to eastern European countries, such as Poland (Norwegian Seafood Export Council, 2009). The United Kingdom, specifically Scotland, is the second largest producer of cultured salmonids within the EEA, at around 150,000 tons, an estimated 38% (WFE) of which is exported (SSPO, 2009). The remainder of fish cultured in Scotland are processed in the United Kingdom along with an additional 40,000 tons WFE which are imported from Norway (in 2008) (Norwegian Directorate of Fisheries, 2009).

The UK salmon processing industry has consolidated over the last 10 years with the number of plants reduced from 145 to 48 but with a slight increase in the number of employees between 2001 and 2008 (Seafish, 2009a). Consolidation has allowed some processors to produce a range of commodities, such as Pinneys of Scotland, who produce smoked fillet, mousses, and ready meals. This trend has the potential for more efficient use of coproduct. Despite opportunities for value addition from within the United Kingdom, over 25,000 tons of the estimated 52,400 tons of processing coproduct from UK farmed fish in 2003 was exported (SEPA, 2004).

Aquaculture coproducts have advantages that they are often more uniform and fresher than those obtained from capture fishery processing (Šližytė et al., 2009). Frequently changing socio-economic conditions and consumer attitudes have led to continual restructuring and a fractured nature of the aquaculture processing industry in the EU, resulting in excessive transportation, diffuse availability and a potential loss in quality of coproduct and potential revenue. Studies have shown that coproducts not only contain significant amounts of omega-3 fatty acids (FAs) (see Table 1 for proximate analysis and references) but substances, such as collagen and peptides (see below) which have potential to yield products of high value.

Currently, companies in Scotland, Norway and Denmark extract the oils from farmed salmon processing coproducts, and produce protein concentrates and oils intended for use in pig or poultry feeds (Thistle Environmental Partnership, 2008). For example, Hordafor, Denmark, produces around 30,000 tons of protein concentrate from around 100,000 tons of aquaculture coproducts per year and also treats mortality waste for biogas production (see below) (Leivsdóttir, 2010 pers. comm.).

Markets for some salmon processing products such as heads are well established in Vietnam and they can be seen for sale commonly in major supermarkets as well as in local markets for around 30,000 VND (about US$1.45) per kilogramme. There is at least one company in the United Kingdom (Ideal Foods Ltd.) which exports aquaculture and fishery coproducts to Asia and other locations. Some Asian countries also import other

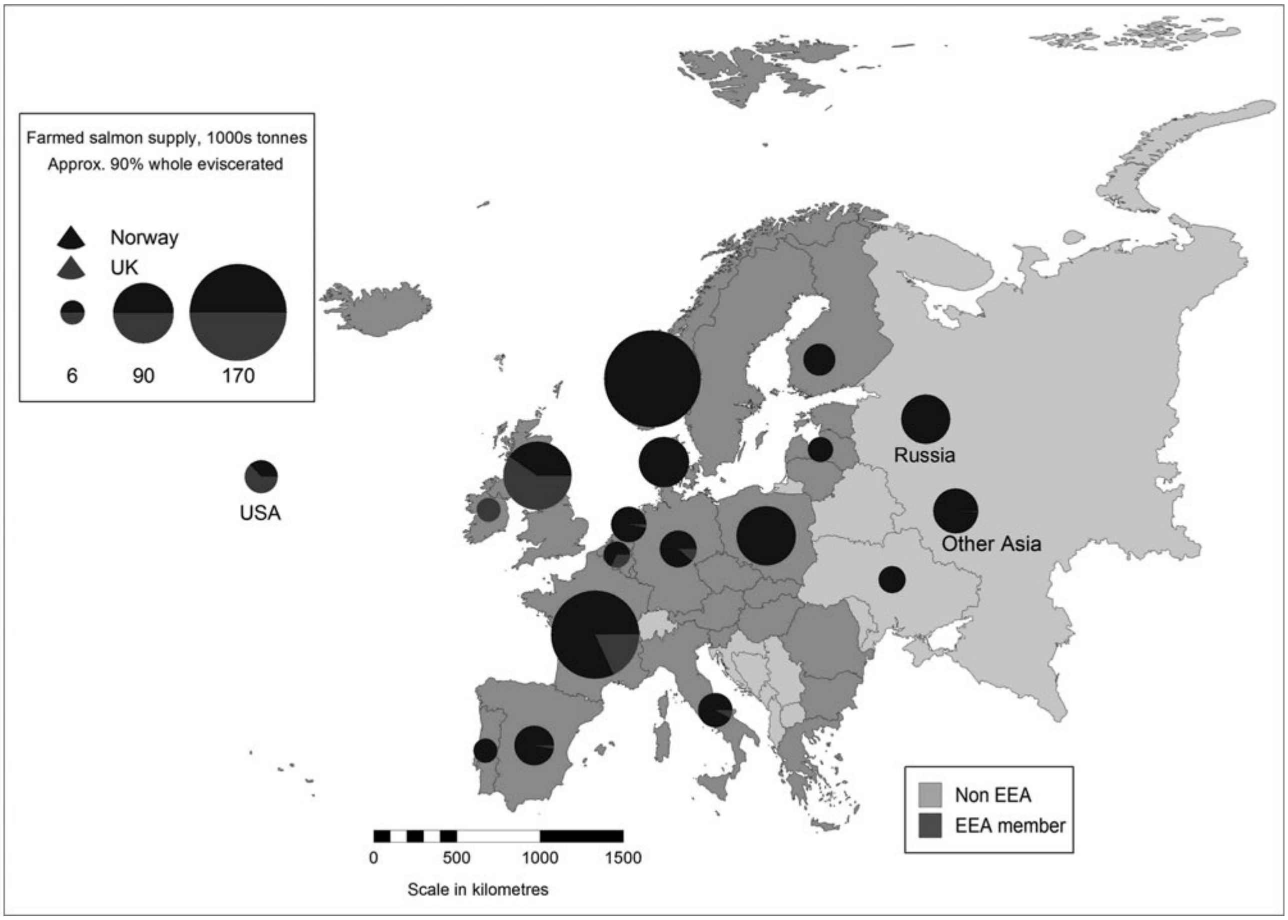

Figure 2 Distribution of farmed eviscerated Atlantic salmon produced in Norway and the UK for further processing during 2008. Source (Norwegian Directorate of Fisheries 2009; SSPO 2010 unpublished data).

livestock coproducts such as chicken feet from the West. The import of coproducts demonstrates different values attached to various animal products by different countries. More research is required to establish the demand for coproducts in various locations and weighed against other value addition options closer to the processing areas.

Although mortalities from production do not enter the human food chain, they have the potential to alleviate the burden on fish meal and oil supplies that are suitable for human food production, by directing them to feeds for pets and other nonlivestock feeds. According to De Silva and Turchini (2008), around 13.5% of the global forage fish catch suitable for fishmeal inputs into human food production was directed to pets and animals farmed for their fur in 2002. Chronic fish mortalities (e.g., sea lice infection) amount to between 5% and 10% of the total salmonid production, for Scotland and Norway (SEPA, 2004; Statistics Norway, 2009). On occasion acute local or widespread catastrophic mortality events occur through disease, algal blooms (Treasurer et al., 2003), jellyfish (SEPA, 2004; Fisheries Research Services, 2010) or extreme weather (SEPA, 2004). A weather or disease event may result in the loss or culling of an entire farm stock of several hundred tons. The slow accumulation of chronic mortalities means they are of little value but schemes such as "The Fallen Stock Scheme" may allow for more efficient collection, lower costs, and better utilization (Bansback, 2006).

Asia

The rapid growth of the aquaculture industry in countries such as Thailand and Vietnam (particularly peneaid shrimp and pangasius catfish, mainly striped river catfish, *Pangasianodon hypophthalmus*) provides an opportunity for comparison of utilization strategies to the European situation. In these Asian countries, producers and processors have developed in parallel and traditionally use a mixture of high and low technology solutions to utilize aquaculture production and processing coproducts (according to stakeholders in the region). The relatively close collocation of production, processing, and support industries in Asia (particularly Vietnam) provide excellent opportunities to formulate efficient resource use management strategies (Figure 3). For the reasons above, these strategies may be logistically more difficult to implement retrospectively in Europe.

Both Vietnam and Thailand are major producers and exporters of penaeid shrimp. In 2007, Vietnam produced 376,700

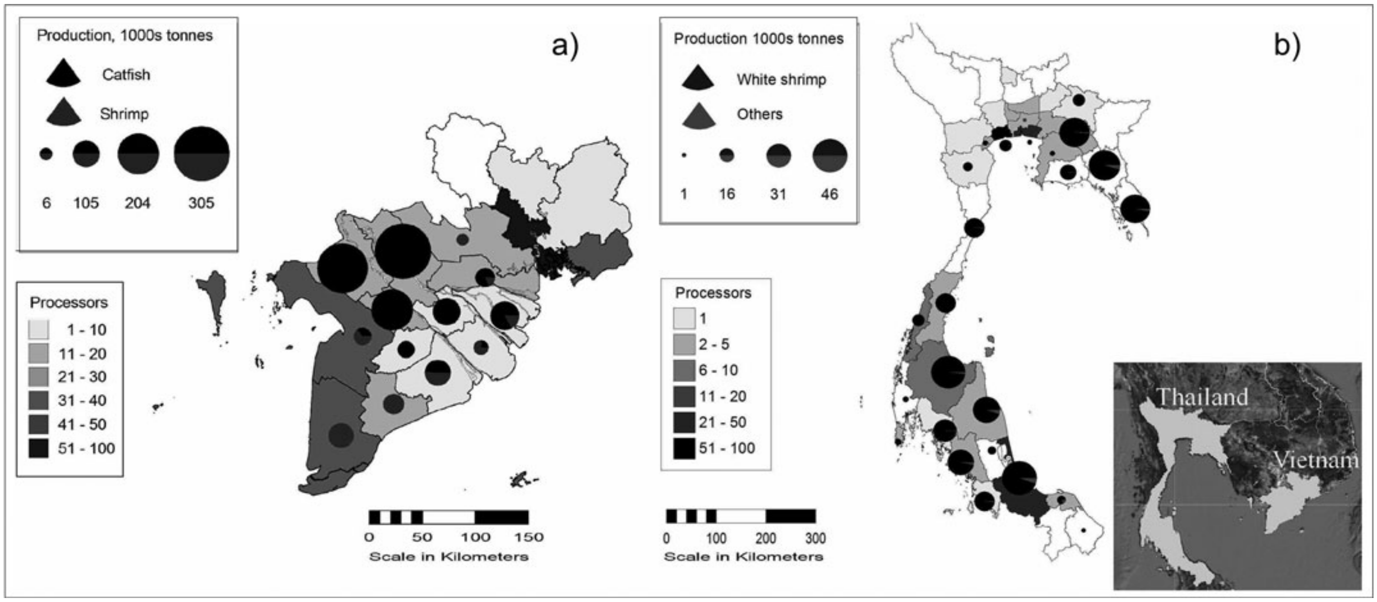

Figure 3 Production and number of processors of a) Pangasius catfish and penaeid shrimp in the Mekong delta of S. Vietnam in 2008b) Penaeid shrimp in S. Thailand in 2007. Source: (VASEP 2010, VIFE 2009, Department of Fisheries (Thailand) 2009.

tons of shrimp, a 10-year increase of over 700%, whereas Thailand produced 501,000 tons which was an increase of more than 120% over 10 years (FAO, 2009b). Thailand remains the biggest exporter of shrimp, exporting almost 374,000 tons in 2010 mainly to the United States of America with around 40% of this preserved or prepared as value-added products such as ready meals or gourmet products (Thai Frozen Foods Association, 2009).

Evidence from processors in Thailand and the Mekong delta show that there is a large variety of shrimp export products ranging from whole to completely peeled and deheaded, for which, complete data were not available. These are raw or cooked but also include partially deshelled and value added. The variety of shrimp products and the changing market makes the amount of coproduct available difficult to assess, although for Vietnam it is estimated at over 150,000 tons (Trang, 2010). Evidence from VASEP (2010) suggests around half of Vietnamese shrimp is being exported whole, mainly to Japan, the United States of America and Europe. Estimates of fillet yields from peneaid shrimp vary but most reliable figures suggest around 50% of the animal is fillet (Table 1) for all species (Benjakul et al., 2009). The vast majority of shrimp mortality occurs in the early stages when the animals are less than 1 g, therefore they tend to be left in the pond and are of little value.

In Vietnam, production of the pangasius catfish has grown from 23,000 tons in 1997 to 1.15 million tons in 2008 (VASEP, 2010). As a consequence, support and fish processing industries have grown rapidly with over 90% of production processed locally for export to over 100 countries as frozen fillets (Lam et al., 2009). However, the expanding industry has also experienced some of the same problems that the salmon industry faced two decades ago. Disease has been a major issue for fish production, resulting in high mortality and consequent use of antibiotics (Lam et al., 2009). Pangasius catfish farms in An Giang province, one of the most intensive production areas on the Mekong delta, commonly report a mortality of up to 30% in the early-to-mid stages of the production cycle, which subsequently drops to around 10% in the later stages of production, despite a reliance on antibiotic-based therapies (Lam et al., 2009). Possible contaminants in mortality flesh from therapeutants may limit the opportunities for value addition, even for pet and fur animal feeds (Nguyen et al., 2006; Lam et al., 2009). Fillet yield for pangasius catfish is low compared to salmon, typically ranging between 30 and 40% (Table 1), depending on the cut. According to some processors, demand is growing for products such as frozen industrial block, regular cuboid blocks which can be further processed more easily. This process results in more trimmings which could be used for many value addition options.

Key informant interviews of pangasius catfish processors in Dong Thap and Can Tho provinces in the Mekong region, coupled with direct observation in local markets in Soc Trang, supermarkets, and restaurants in several other Mekong provinces revealed that postfilleting products are commonly on sale for consumption. These included the catfish stomachs and heads. According to Nguyen (2010), this is around 5% and the rest is processed into fishmeal and oil, including viscera, heads, skins, and trimmings (Le Nguyen, 2007). Fifty-three percent (53%) of fish meal from coproducts is directed to terrestrial livestock feeds, and 45% for domestic aquaculture, with the oils separated for further sale (Nguyen, 2010). However, traceability can sometimes be lost (Le Nguyen, 2007) possibly resulting in intraspecies feeding of exported products. Tacon (2002) suggested that some shrimp coproduct may still be used to produce shrimp feed and is preferred by some farmers. Although these coproducts provide a readily available protein supply for livestock,

Table 2 Summary of EU by product categories and regulations on their uses. See below for descriptions of various processes allowable under ABPR

Category	Byproduct	Allowable uses under ABPR
1.	No fish byproducts in Cat. 1	
2.	• Fish farm mortalities irrespective of cause • Fish parts collected from the effluent of Cat. 2 processing plants • Fish parts that contain excessive amounts of veterinary residues • Cat.3 material that may have been contaminated with Cat. 2.	• Incineration on site or at approved facilities • Processed in accordance with other ABPR provisions but not for livestock feeds, cosmetics or medicinal uses • Feeds for fur, zoo and circus animals • Ensiled, composted or used in biogas plants, meeting hygiene and biosecurity measures in the annexes of the ABPR • Disposed of in landfill if special derogations are applicable
3.	• Parts of slaughtered animals considered unfit or not intended for human consumption • Fish caught for fishmeal production • Coproducts from fish processing plants	• Incineration on site or at approved facilities • Ensiled, composted or used in biogas plants, meeting hygiene and biosecurity measures in the annexes of the ABPR • Processed in accordance with other ABPR provisions including "technical purposes" such as pharmaceuticals and cosmetics • Used to make livestock feeds but must not be made into fishmeal for feeding fish unless from wild sources

Source: European Commission 2002, 2003.

they could perhaps be redirected to other industries providing products of more value.

Some farmers also revealed that fresh mortalities may sometimes be consumed by farm employees or sold to local markets. While this would be highly unacceptable in the European Union, it is commonly accepted in Vietnam but it is thought that in most cases mortalities are being buried. According to evidence from stakeholders, occasionally, mortalities were reported to be fermented for fertilizer for use on local farms or on the site itself in small quantities for fruit production.

ANIMAL BYPRODUCT REGULATIONS, LEGISLATION AND STANDARDS

The further consumption, processing, recycling, transport, and traceability of aquaculture coproducts, byproducts, and mortalities from aquaculture and capture fisheries within the EEA is controlled by the European Animal By-Product Regulations (ABPR)[1] and subsequent amendments[2] (European Commission, 2002, 2003). These regulations control the use of animal products which are not intended for human consumption in order to maintain biosecurity, eliminate contamination of food and animal feed, and maintain general hygiene. In particular, they forbid the use of coproducts from cultured fish processing in the manufacture of fishmeal for the feeding of other cultured fish, even of different species (European Commission, 2003). This is because of fears over transmissible spongiform encephalopathies (TSEs). The byproduct categories and their allowable uses are summarized in Table 2. There have been suggestions that the ABPR are inappropriate for aquaculture (Thistle Environmental Partnership, 2008) as there is no evidence of TSEs within fish (FAO, 2002b) and catastrophic mortalities due to nondisease events could perhaps be better utilized if there were no biosecurity risks. In addition, ABPR do not definitively state at what point postfilleting products become coproducts or byproducts, not intended for human consumption. There are many parts of the fish that could be directed to human consumption at the filleting stage including cheeks, bellies, and other off-cuts (Ramírez, 2007).

Category 3 byproducts, including coproducts from fish processing, have many more options open to their use than Category 2 products, such as fish mortalities. At present, Category 3 coproducts can be used in nonfin fish feeds and for human pharmaceuticals which Category 2 coproducts cannot. In addition to feeds for animals not intended for human consumption, ABPR Category 2 or 3 material may be incinerated, composted in closed containers or used in a biogas production plant (anaerobic digestion) but must meet other criteria stipulated in the ABPR (European Commission, 2002). See Table 2.

From stakeholder and key informant interviews in Vietnam, regulations in many Asian countries seem to be less strict or at least less strictly enforced, and there is often a more ad hoc approach to waste disposal and coproduct use. Certification schemes are beginning to acknowledge these issues such as the WWF Aquaculture Stewardship Council dialogues on production standards (WWF, 2008, 2009, 2010). Coupled with regulations imposed by importing nations local regulations may be tightened and more strictly enforced. If the WWF standards are widely adopted, the future intraspecies use of processing coproducts for feeds will be strictly prohibited whereas disposal of catfish mortalities will be limited to fertilizing or "fermentation," as well as the European method of incineration or burial (WWF, 2009). While this may improve traceability and biosecurity overall, some resource efficiency may be lost until more technologically advanced solutions are available.

DISPOSAL OPTIONS FOR CATEGORY 2 MORTALITIES AND BYPRODUCTS

As the EU ABPR do not allow for mortalities to enter the human food chain, their disposal options are not discussed here

[1]ABPR, Regulation (EC) No 1774/2002
[2]Regulation (EC) No 811/2003

Table 3 Summary of costs, level of expertise, and value addition from options available to mortalities falling into Category 2 of the ABPR

Method	Level of capital investment	Level of expertise	Operating costs	Value of product	Pathogen deactivation	Comments
Ensiling[1]	Low	Low	Low	Very low	Some	Interim storage
Feeding to animals[2]	Low	Low	Low	Low	If cooked	Quality can be too poor
Onsite incineration[3]	Low	Low	Medium	None	Yes	High air pollution
Landfill[3]	None	Low	High	None	No	Biosecurity risk
Composting[4]	Low	Medium	Low	Low	Yes	Unsuitable for large numbers
Anaerobic digestion[5]	High	High	Low	High	Thermo-phillic only	Markets not well established for liquid products

Source: 1. Arason et al., 1990; Carswell et al., 1990; Smail et al., 1993; Lückstädt, 2008, 2. Thistle Environmental Partnership 2008; 3. Glanville et al., 2006; Thistle Environmental Partnership 2008; Local Government association 2008, 4. Glanville et al., 2006; Smail et al., 2009; Inter Trade Ireland 2009, 5. Seafish, 2008; He, 2010; Méndez-Acosta et al., 2010; Inter Trade Ireland 2009.

in detail, although a summary of available options can be seen in Table 3. Ensiling is often used to store farm mortalities and also postfilleting coproduct before transportation for further processing. Ensiling usually involves maceration and storing in plastic containers, using organic acids at about 2 to 3% v/v to encourage autolytic hydrolysis, for interim storage before further treatment or disposal. The process prevents spoilage and odours, and avoids attracting vermin (Arason et al., 1990; Carswell et al., 1990; Lückstädt, 2008). Ensiled product using organic acids can be used as pig and other livestock feeds (Carswell et al., 1990; Lückstädt, 2008) but acceptance from these industries can be low (Arason et al., 1990). Organic acids are generally preferred in all countries, not only because they can be fed to animals, but because they are less corrosive to equipment and less dangerous to handle than inorganic acids (Carswell et al., 1990). The product can also be used as a fertilizer if used with other ingredients (Prescott et al., 1997). These options may also be useful for Category 3 coproducts in remote locations, for example, where higher value addition options may not be feasible. Ensiling is not generally used as a storage method of shrimp but Cao et al. (2009) showed that it could be used to extract protein from coproducts for further use.

VALUE ADDITION OPTIONS AVAILABLE TO CATEGORY 3 PROCESSING COPRODUCTS ONLY

Fish and Shrimp Meals

Aquaculture has often been condemned for its use of commercial fisheries products in aquafeeds, although its use in aquaculture has not increased significantly for the last 10 years (Figure 1). However, global supply is unstable and has led to increasing prices on the global market (FAO, 2009b). The burden on the fishmeal industry can, therefore, be lessened by supplying coproducts from aquaculture for use in terrestrial livestock feeds, which would normally be sourced from the reduction industries. Pig and poultry feeds include reduction fishmeal, containing between 6 and 10% oil (Seafish, 2009b), because of the health benefits of omega-3 FAs to both the livestock and human consumers (see below) (Fishmeal Information Network, 2001; Kouba and Mourot, 2010). Though pangasisus catfish are naturally high in protein, they are low in omega-3 (Polak-Juszczak, 2007), meaning in Vietnam relative performance of livestock may be better with a fishmeal source high in omega-3. Nguyen (2010), showed that pigs fed diets containing catfish coproduct performed well or better in terms of diet intake, growth, meat quality, and mortality, than diets which included traditional fish meal sources but commercial data is not available. Figure 5 shows the main methods currently employed in coproduct utilization for the named species.

Although the EU ABPR forbid the use of farmed fish coproducts in fin-fish feeds, the regulations will apparently allow them to be used in shrimp diets or vice versa. Studies have shown that capture fishery coproducts can be used in shrimp feeds with good results (e.g., Sudaryono et al., 1996). Use of fin-fish byproducts from capture fisheries have also been used in trials for aquafeeds for other fin-fish species by Goddard et al. (2008), Whiteman and Gatlin (2005) and Seoka et al. (2008) amongst others. The results for these studies were mixed.

Shrimp meal has been shown to perform less well than fishmeal when included in aquafeeds (e.g., Hardy et al., 2005; Whiteman and Gatlin, 2005). This is attributed to poor availability of protein (Coward-Kelly et al., 2006; Sachindra et al., 2006). Although shrimp coproduct has protein levels of 35 to 50%, much is bound to highly indigestible chitin (15 to 25% dry weight) (Edwards, 2004; Sachindra et al., 2006) and 10 to 15% as minerals (Sachindra et al., 2006). Digestibility can often be improved by separation of the chitin by hydrolysis or fermentation (Nwanna, 2003; Coward-Kelly et al., 2006). Autolysis at ambient temperatures has generally given low yields of usable products. However Cao et al. (2009) showed that autolysis of shrimp heads using gradual increase in temperature up to 70°C could give protein recovery rates of 88.8%, which can then be used for animal feeds or flavorings for human consumption (see below).

Fish Oils

In recent years, there has been much emphasis on the health benefits of consuming oily fish as part of a balanced diet, not least because of high omega-3 polyunsaturated fatty acid

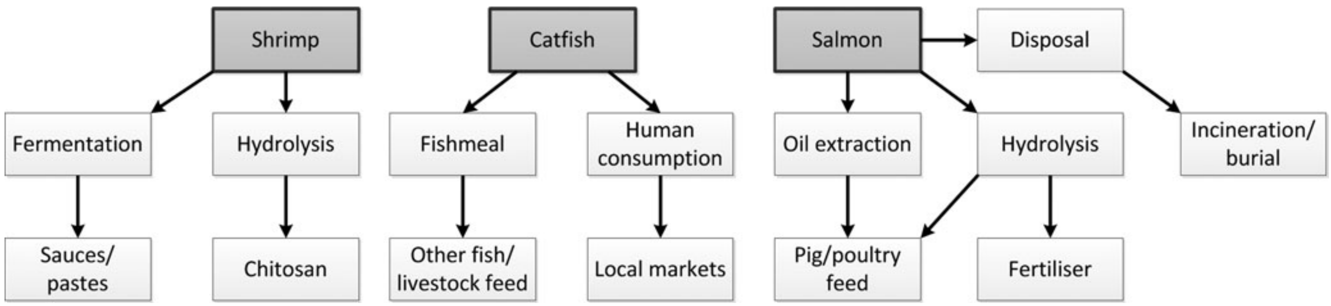

Figure 4 Main routes for utilisation of processing co-products from cultured Atlantic salmon, Pangasius catfish and peneaid shrimp currently employed in the EEA and SE Asia. Source: Le Nguyen 2007; SEPA 2004 and Stakeholder interviews in the Mekong Delta, Vietnam and S. Thailand.

(PUFA) contents, eicosapentaenoic acid (EPA), and docosohexaenoic acid (DHA) which are limited to marine sources. Studies have shown that maintaining a level of omega-3 to be important in reducing factors associated with heart disease (Holub and Holub, 2004; Domingo, 2007), strokes, thrombosis, mental health problems and arthritis (Sun et al., 2002). More recently a high ratio of omega-3 FAs (including EPA and DHA) to inflammatory omega-6 fatty acids, common in many plant oils, has also shown to be important in human health, particularly in preventing coronary heart disease (Holub and Holub, 2004). In animal nutrition, inclusion of long chain omega-3 in pig diets has been shown to improve survival substantially for weaning and suckling pigs and is, therefore, an important dietary component (Fish Information Network, 2001). At present much of this omega-3 comes from commercial fishmeal (Seafish, 2009b). However, if necessary, fishmeals with low omega-3 content from pangasius catfish coproducts, for example, could be supplemented with oils extracted from salmonid coproduct or other high omega-3 product.

Concentrations of lipid and in turn of EPA and DHA in farmed salmon viscera are higher than those of the fillet (Sun et al., 2006), and of many wild captured fish (Figure 4), although this will depend on the diet of the farmed salmon. A proportion of Scottish salmon, perhaps 10%, are fed higher levels of fishmeal and fish oil than in other locations to meet consumer demand (Tacon and Metian, 2008). Consumer fears over

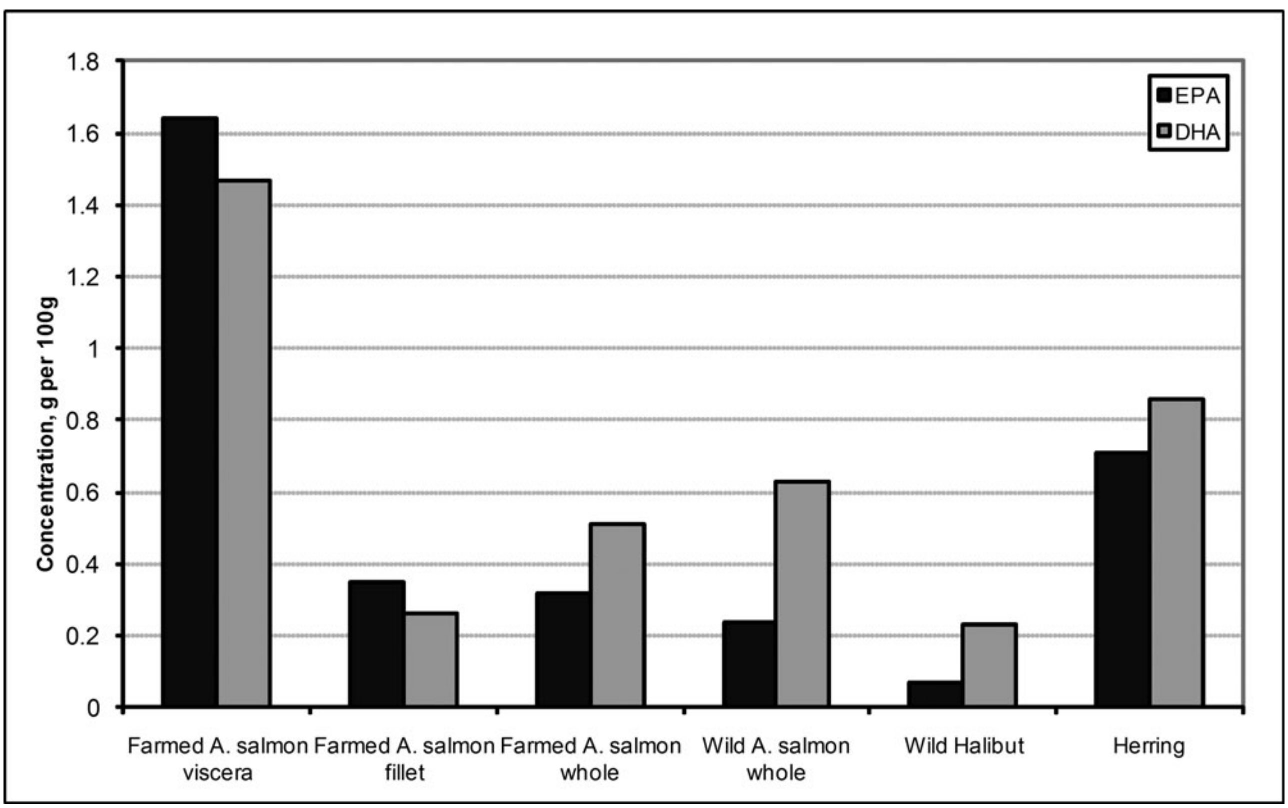

Figure 5 EPA and DHA concentrations in the viscera of farmed Atlantic salmon, compared with whole wild and farmed salmon and other commercially important species. (See Table 1 for total lipid and omega-3 contents in the studied species). Adapted from Sun *et al*. 2006.

contamination in farmed salmon with persistent organic pollutants (Hites et al., 2004) and heavy metals (Domingo, 2007) may lead to further fears over bioaccumulation if oils are concentrated for health supplements or recycled for animal feeds. Contaminant levels are generally regarded as being below levels considered to be dangerous to human health (COT, 2006; Fernandes et al., 2009) and often the refining process removes many persistent contaminants (Muggli, 2006), especially the deodorization process using steam distillation, but this may destroy valuable fractions such as carotenoids (Hilbert et al., 1998). Salmonid visceral oil is of lower quality than that of muscle's in terms of lower phospholipids, antioxidants α-tocepherol, and total carotenoid concentrations (Zhong et al., 2007) but despite this, visceral oil is less subject to oxidation than muscle oils (Sun et al., 2006) and aquaculture coproducts can often be supplied fresh (Šližytė et al., 2009). Oils are already extracted from salmon coproducts by simple heating, decanting, and clarification by centrifuge, in Denmark by Hordafor, Norway by Scanbio Ltd., and the United Kingdom by Rossyew Ltd. who also filter the oil for a purer product. However, the full potential is not being met. More research is required to determine the markets for the products and where oils can best be directed. Also, yields can be improved and the omega-3 fraction separated to higher purity (Sun et al., 2002) although this may not be cost effective.

Whereas it is important to maximize the use of omega-3 FAs to relieve the burden on commercial fishmeal and oil reduction industries, the low omega-3 content in pangasius catfish fat may mean that other industrial uses may be more appropriate. If cost effective, these applications can also contribute to resource efficiency of fishmeal and other global inputs within and without the pangasius catfish value chain. Fish oils have traditionally been used in the tanning industry for the production of high quality leather such as chamois, and this is a possible route for oils produced from mortalities (Thistle Environmental Partnership, 2008). Worldwide, there has been increasing interest in biofuels as an alternative to fossil fuels, but this has been tempered with concerns over deforestation and diversion of food products toward the biofuel industry (Sachs, 2007; Piccolo, 2009). Recent activities have shown catfish coproducts in Vietnam and tilapia coproducts in Honduras to produce excellent biofuels. Research into using fish coproducts and mortalities from the pangasius catfish industry has been gathering pace (Nguyen D.A.T. et al., 2009; Nguyen T.V. et al., 2009; Piccolo, 2009). Fish oils have been reported to be excellent fuels because they can be used in unmodified diesel engines and a high yield can be obtained from the raw product (Piccolo 2009). Initial attempts produced fuels which released emissions which were harmful to human health, but the quality has now improved (Nguyen D.A.T. et al., 2009).

Fish fat can be broken down into functional biofuels by simple processes on small or large scales with glycerine as a further coproduct that has applications in a number of industries, e.g., cosmetics (Piccolo, 2009). The oils may be further purified into fuels of more specific character and use as outlined by Wiggers et al. (2009), Wisniewski Jr. et al. (2009), and Preto et al. (2007), and which may meet European Quality Standards for biofuels, although this needs further attention. According to Nguyen D.A.T. et al. (2009), between 2005 and 2007 the price of pangasius catfish fat increased from between 2,000 and 3,000 VND (US$0.10 to $0.14) per kg to about 6,000 VND ($0.28) per kg due to interest in producing biofuels and there are now established processing plants in An Giang and Can Tho. The Can Tho plant has a capacity of around 50 tons per day of raw material and was exporting its product to Singapore at 11,000 VND (about US$0.60) per liter in 2005 (Agriviet.com, 2009). Although there is no specific mention of using mortalities or fish coproducts for biodiesel production in the EU ABP regulations, the allowance for biogas production and industrial uses should permit this route which could be of particular interest to remote or small scale fish-farms and processors in the EU.

Sauces, Pastes and Other Products for Human Consumption

In Europe and other Western countries, direct consumption options for humans are likely to be limited because of customer perception, compared to Vietnam and other Asian countries which import processing coproducts from the West for human consumption. It is difficult to trace the coproducts, which are available for value addition from European salmon because of the diffuse nature of processing and, therefore, the various fractions in each of the major processing countries. The acceptability of products to European consumers may differ to their Asian counterparts and the nature of value-added products will depend on the quality of the flesh which can be obtained from the trimmings, etc., and may only allow for commodities such as fish-balls, mousses or pâtés to be produced (Young, 2010 personal communication).

In Thailand, Vietnam, and many other Asian countries, utilization of shrimp coproducts from small capture fishery species such as krill is fairly well established as fermented goods for human consumption (Sobhi et al., 2010). There is also an established market for *mungoon*, a shrimp paste made from the cephalothorax (Binsan et al., 2008). Mungoon is a highly nutritious and healthy food because of high omega-3 FAs, essential amino acids and calcium ions according to (Binsan et al., 2008). Despite this usage, the yield of mungoon using traditional production methods is low, reported at 21.5% of raw material (Benjakul et al., 2009), leaving substantial amounts of further coproduct that requires further processing into useful products or disposal.

In Vietnam, most Pangasius catfish production is directed toward frozen fillets, but there is also a market for fish sauces, pastes, and surimi to which some coproducts, such as trimmings and undersize fish, are directed (Le Nguyen, 2007). Gelman et al. (2001) and Glatman et al. (2000) described possible techniques for fermenting fish, using strains of lactic acid bacteria, similar to the traditional techniques for mungoon, to produce novel "meat-like" products which could be acceptable to consumers.

Collagen and Gelatin

Collagens are the most abundant proteins in vertebrates, commonly found in connective tissues, especially of the skin but also bones. There are at least 26 forms (Li et al., 2005) of which the most abundant and most useful for biomedical and cosmetic applications is type I (Lee et al., 2001; Li et al., 2005). Its usefulness stems from the ease of its extraction in solution and that it can be shaped into many forms containing tensile fibers which are biodegradable, biocompatible, and nonantigenic (Lee et al., 2001). These can be used in many applications including multiple medical uses such as drug delivery and wound dressings, cosmetics, and edible food coatings (Lee et al., 2001; Singh et al., 2011). Collagen extracted from fish swim-bladders, commonly called isinglass, has traditionally been used to clarify beer, (Hickman et al., 2000; Regenstein and Zhou, 2007). Extraction from terrestrial animals is well established, however fish skins also provide excellent potential for extraction and has been described by Singh et al. (2011), Sadowska and Kolodziejska (2005), Muyonga et al. (2004), Aidos et al. (1999) and Eckhoff et al. (1998) among others. Although yields from fish skins are generally higher than mammalian (Yunoki et al., 2003), there are differences in structure and amino/imino acid sequences which can change the properties of fish collagens compared to higher vertebrates. Denaturation temperatures are generally lower for fish which may affect their uses, particularly for human biomedical applications (Nagai and Suzuki, 2000; Yunoki et al., 2003, 2004; Saito et al., 2009), but more work is needed to investigate how the different properties can best be applied. The thermal stability of collagen is generally higher in tropical species and according to Singh et al. (2011), pangasius catfish collagen has a maximum temperature threshold of around 39.5°C, similar to that of commercial porcine collagen. Collagen with lower thermal stabilities, such as that from salmon, reported as about 19°C for chum salmon (Yunoki et al., 2003), can be improved by techniques such as UV irradiation without risking toxicity that chemical techniques may encounter (Yunoki et al., 2003).

In most extraction studies, fish collagen was split between acid and pepsin soluble fractions. Singh et al. (2011) described methods to extract collagen from pangasius catfish skins similar to other collagen extraction techniques, using NaOH to first extract noncollagen proteins followed by neutralization and dissolving in acetic acid. The acid soluble collagen can then be precipitated using NaCl and the further fractions obtained from the filtrate using pepsin hydrolysis to give a combined yield of 12.8% (wet skin weight).

Gelatin is a mixture of proteins prepared from the breaking of cross-linkages and denaturation of collagen but otherwise is similar in amino/imino-acid composition to the parent collagen (Regenstein and Zhou, 2007). Although less valuable per unit weight, it has vast opportunities for halal and kosher food applications, most commonly in various sorts of gels for texture, stabilization, emulsification, and alternatives to fats (Karim and Bhat, 2009). Fish gelatins of cold and warm water fish, and terrestrial sources have certain tradeoffs against one another. Lower melting points of fish gelatins are an issue, and therefore those from warm water fish with higher melting points may be of more value, possibly due to higher imino acid content (Muyonga et al., 2004; Karim and Bhat, 2009; Shahiri Tabarestani et al., 2010). However, a major application of gelatins has been in chilled desserts which could perhaps favor lower melting point fish gelatins because of better release of flavors and aromas (Choi and Regenstein, 2000; Boran et al., 2010) and offer alternative product options because of different textures and properties (Zhou and Regenstein, 2007). Some additives such as neutral salts (Sarabia et al., 2000), sugars (Choi and Regenstein, 2000), egg albumen (Badii and Howell, 2006) or treatments with transglutaminase (Yi et al., 2006) may improve properties but uncertainty exists over the kosher/halal status of enzyme treatments (Karim and Bhat, 2009). Thermal stability is of importance in the manufacture of drug and food supplement capsules, which has been suggested as another possible application for fish gelatins with lower melting points (Karim and Bhat, 2009). Other applications include possible biomedical uses such as biocompatible films and fibers with similar properties to collagen, possibly combined with other biopolymers such as chitosan described below (Yi et al., 2006). The most desirable qualities for all applications are high gel strength, viscosity, and rheological properties, given particularly by the amino/imino acid contents and lower content of low molecular weight fractions (Eysturskarð et al., 2009; Karim and Bhat, 2009; Badii and Howell, 2006) but also higher gelatin concentration and maturation temperature, i.e., that at which the gel is allowed to set (Choi and Regenstein, 2000). The intrinsic physical properties also tend to be inferior for (especially cold water) fish compared to mammalian sources, but the extraction process can also have a significant influence over the quality of the gelatin (Boran et al., 2010; Shahiri Tabarestani et al., 2010). Generally, it is extracted by one of two processes, the acid or the alkaline process, referring to the pretreatment phase, to produce type A or type B gelatin, respectively. Low storage and pretreatment temperatures are generally thought to preserve the integrity of fish gelatin and provide better yields, especially of cold water origin which are subject to quicker degradation than mammalian gelatin (Giménez et al., 2005a; Regenstein and Zhou, 2007; Karim and Bhat, 2009). Pretreatment is usually followed by hydrolysis in mild organic acids at moderate temperatures of around 45°C (Giménez et al., 2005b; Karim and Bhat, 2009). The alkaline process has advantages in removing more noncollagenous protein and the following acid neutralization allows for a weak acid extraction which minimizes damage and gives high yields of good quality gelatin (Regenstein and Zhou, 2007; Shahiri Tabarestani et al., 2010). Barriers to the production of fish gelatins cited by Karim and Bhat (2009) were possible fishy off-flavors and odors in some species, and problems with availability of large amounts of consistent raw material, therefore economy of scale. If any problems of fishy flavor and odor are sufficiently addressed, there is vast potential for collagen and gelatin extraction from the pangasius catfish industry within the Mekong delta which produces large amounts of consistent coproduct and has the infrastructure to provide fresh material and overcome economy of scale difficulties. In Europe, niche markets for cold water fish gelatins may be less interesting and may not be able to compete with porcine or bovine sources.

Chitosan and Glusosamine

Chitosan is a polysaccharide which is most commonly made from the deacetylization of chitin from crustacean shells but must first be separated from the protein and mineral complex. Chitosan is an attractive material because it is biodegradable, biocompatible, exhibits antimicrobial and haemostatic properties, binds protein and fats, and is soluble in weak acids (Shahidi, 2007). Chitosan has many commercial applications depending on the properties provided by the raw material, the processes used to achieve different degrees of deacetylization (DD), the molecular weight of the product, and polyectrolytic properties (Synowiecki and Al-Khateeb, 2003). Applications include disease-resistant coatings for agriculture and maintaining freshness of produce, in industrial polymers used for paper and textiles, halal and kosher cosmetics, and medical purposes such as wound dressings, slow-release drug, and encapsulation technologies. It is also commonly marketed as a slimming aid (Percot et al., 2003; Synowiecki and Al-Khateeb, 2003; Aye and Stevens, 2004; Coward-Kelly et al., 2006; Lallemont, 2008). Commercial processes for its production from aquaculture coproducts are already well established and usually involves treatment of shrimp shell with acids to demineralize the calcium content, alkalis to separate the chitin from the protein and finally deacetylization of the chitin to produce chitosan (Synowiecki and Al-Khateeb, 2003). Properties given by high DDs are considered more valuable outlined by Lertsutthiwong et al. (2002) and Synowiecki and Al-Khateeb (2003) among others but this requires several deacetylization steps with washing and drying between each, and high levels of control at each point (Lallemont, 2008). The quantities of chemicals used have caused environmental concerns (Aye and Stevens, 2004; Pacheco et al., 2009; Trang, 2010) and can adversely affect the product (Arment and Guerrero-Legarreta, 2009). Therefore, interest is toward techniques such as enzymatic hydrolysis which are potentially more predictable, less damaging to the product and environment, and that separate protein and carotenoid fractions for further use (Synowiecki and Al-Khateeb, 2003; Aye and Stevens, 2004; Coward-Kelly et al., 2006. More research is required to weigh the various advantages and disadvantages over traditional methods on economic and environmental basis (Synowiecki and Al-Khateeb, 2000; Percot et al., 2003).

The growth in shrimp culture has led to an increase in the availability of raw material for chitosan production making it more economically attractive (Coward-Kelly et al., 2006). Chitosan production is low in Vietnam because of environmental concerns and technological barriers relating to the quality of the product (Trang, 2010). However, it exports a small proportion of chitin and shell from shrimp processing to China for chitosan production which is then further exported worldwide. Evidence from interviews with Vietnamese shrimp processors also suggests a growing chitin industry in Vietnam but it is losing the potential to create huge revenues, as the price for chitosan is between \$30 and \$150 US per kg, compared to \$3.60 and \$6 per kg for chitin (Pichyangkura, 2010). Thailand has a well-established chitosan industry and dedicated research into its applications, though more work is needed to establish these markets and assess how they may compete with alternative products such as collagen for some applications. Currently, around 70% of the chitin produced is transformed into less valuable glucosamine products, 10% into oligosaccharides and only 20% into chitosan (Lallemont, 2008).

Glucosamine is a health supplement which is widely available in several forms in the United States and Europe. It is marketed for alleviation for osteoarthritis as it is thought to promote the formation and repair of cartilage (Lallemont, 2008). It is formed from the hydrolysis of chitin usually by the action of acids. The process does not require the same level of control as chitosan production, though it follows the same initial steps to produce chitin which is then hydrolysed by the action of acids. The accessibility of the technology and the developed international markets result in it being more favored by industry than chitosan, but this may change as more applications for chitosan become apparent, particularly for valuable medical applications mentioned above (Lallemont, 2008).

Fish and Shrimp Peptides

Hydrolysis techniques are well established in other industries and are gaining interest in the aquaculture and fisheries industries for the abstraction of peptides from marine products. The resulting mixture of peptides is referred to as a protein hydrolysate. Peptide production by ensiling is unpredictable (Cancre et al., 1999) because of many different endogenous enzymes, and the low pH may destroy some valuable nutritional elements (Lian et al., 2005) leading to bitter tasting peptides with unpredictable properties that may be unsuitable for many applications (Hevrøy et al., 2005). Therefore, more predictable and controllable forms of hydrolysis are required for the production of peptides of particular size and character, which determine specific properties (Hevrøy et al., 2005; Bourseau et al., 2009; Vandanjon et al., 2009). This requires commercially available enzymes in controlled conditions which can give more predictable results than endogenous enzymes. There are a huge number of applications for fish protein hydrolysates including bio-active supplements, health food supplements, food additives (e.g. emulsifiers and foaming agents), animal feeds and cosmetics outlined by Thorkelsson and Kristinsson (2009) and Kristinsson and Rasco (2000) among others. Valuable peptides can be extracted from fish heads, trimmings, bones, viscera, shrimp shells, and heads. The processes have been well studied, but documentation and verification of health claims, with regard to rigorous in vivo investigation and many marketing aspects to achieve full commerciality still need to be addressed (Raghavan and Kristinsson, 2009; Thorkelsson and Kristinsson, 2009).

The properties given by various peptides is huge and beyond the scope of this review but smaller peptides (of high degrees of hydrolysation) are generally more desirable for flavorings and larger peptides for foaming agents and emulsifiers (Kristinsson and Rasco, 2000; Šližytė 2009). The effect that various conditions have on the size and character of final products of some fish hydrolysates and their uses is outlined by Bourseau et al. (2009), Cancre et al. (1999), Kristinsson and Rasco (2000), Thorkelsson and Kristinsson (2009) and Kim and Mendis (2006). Human health benefits of fish peptides are generally attributed to high antioxidative properties (Dong et al., 2008) and are given by He et al. (2007), Hong and Secombes (2009), Je et al. (2004), and Marchbank et al. (2009) among others. Methods of filtration and separation for purifying hydrolysates are given by Bourseau et al. (2009), Vandanjon et al. (2009), and Thorkelsson and Kristinsson (2009).

There are many publications which investigate the feasibility of feeding hydrolysates from fish and seafood coproducts to fin-fish aquaculture species (Gildberg et al., 1995; Hevrøy et al., 2005; Aksnes et al., 2006) among others and shrimp (Córdova-Murueta and García-Carreño, 2002) with varying success. This poses many opportunities for value addition, but strict biosecurity and traceability measures would be necessary. Salmon hydrolysates and protein concentrates are already produced commercially in conjunction with oils, by the companies mentioned above, for use in the animal feed industry.

Carotenoids (Astaxanthin and Canthaxanthin)

Shrimp and salmonid coproducts also contains significant amounts of carotenoid, mostly astaxanthin or canthaxanthin at around 24 g per ton in cultured *P. monodon* (Babu et al., 2008) and up to 7.5 g per ton in salmon viscera (Czeczuga et al., 2005). Carotenoids are powerful antioxidants and, therefore, have many beneficial properties in human and animal nutrition (Lorenz and Cysewski, 2000; Pacheco et al., 2009). It is also used as a pigment in cosmetics (Armenta and Guerrero-Legarreta, 2009).

Synthetic astaxanthin is used as a pigment in animal feeds, particularly for salmonids (Lorenz and Cysewski, 2000; Sachindra et al., 2006) at about 5 kg per ton (Synowiecki and Al-Khateeb, 2003) as flesh color is important for salmonid marketing. However, no significant difference was found between uptake and deposition of synthetic astaxanthin and natural astaxanthin in salmonid feeds (Lorenz and Cysewski, 2000). Therefore, natural astaxanthin has no advantage within aquafeeds and is unlikely to be able to compete with synthetic ingredients, although there could be a niche in the organic aquafeed market. However, concentrations are far less than in the alga *Haematococcus pluvialis*, which commercially grown can contain as much as 30 kg per ton (Guerin et al., 2003). Therefore, extraction of astaxanthin from shrimp and salmonid coproducts is only likely to be cost-effective if it is removed during the processing of other valuable products, but it may be able to add value to salmon oil health supplements if retained during the extraction process.

Extraction can be combined with chitosan production (Armenta-López et al., 2002) and some studies have shown that acids, commonly used in the chitosan industry, may increase the yield of astaxanthin because of reduced oxidation. However, excessively aggressive acid and alkali treatments can adversely affect the carotenoid (Armenta-López et al., 2002; Sachindra and Mahendrakar, 2005; Sachindra et al., 2006; Pacheco et al., 2009). Most promising methods, both economically and environmentally, therefore, are those which can combine mineral, chitin, protein, oil, and carotenoid separation and extraction in the various processes outlined above (Armenta-López et al., 2002; Synowiecki and Al-Khateeb, 2003; Coward-Kelly et al., 2006; Pacheco et al., 2009).

Natural astaxanthin of 60 capsules containing around 4 mg from *H. pluvialis* commonly sell for around US$20 on the Internet, therefore there is commercial potential for natural substance from a number of aquaculture sources including shrimp and salmon coproduct.

CONCLUSIONS

Aquaculture coproducts are under-utilized in many parts of Europe resulting in lost profits and potential environmental impact through waste disposal. In Asia, coproducts are used for production of value-added commodities but probably not to their full economic potential. In addition, their current utilization could be posing risks to the environment, human health, and biosecurity.

Aquaculture coproducts have the potential to supply quality fishmeal and oils to terrestrial livestock feeds, thus alleviating some of the pressure on the reduction industries. They may also be directed toward food additives, high-value health supplements, and cosmetic industries that are acceptable to most religious groups, in some cases providing a lucrative side industry. They have significant advantages over capture fishery coproducts in that they can be supplied fresh and in a consistent form. However, for many, further research is needed to support medical claims and develop markets for their full economic potential to be met.

With regard to aquaculture mortalities, ABPR has proven a barrier in many circumstances. However, research has shown that there are other uses for mortalities which have greater biosecurity and are kinder to the environment, reducing impacts and burdens on resources. These strategies may not only reduce costs but provide income if logistical and legislative barriers are overcome. More research is required to evaluate these different technologies for resource efficiency in economic and environmental terms. There are many economic and environmental assessment tools which could do this such as standard Cost Benefit Analysis approaches in conjunction with Life Cycle Assessment and other environmental impact modeling tools.

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