The potential of fish and fish oil waste for bioenergy generation: Norway and beyond

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The potential of fish and fish oil waste for bioenergy generation: Norway and beyond

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This article examines the potential of fish waste for liquid and gaseous biofuels, with focus on Norway but also some consideration of other markets. Fish production and processing wastes are a significant source of material for bioenergy production. Norway is a country of high fish production, but currently low development of the bioenergy sector due to the ample availability of hydropower. World fish consumption per capita nearly doubled over the last 45 years. The resulting increase in fish processing wastes and the expansion of the renewable energy market imply that fish processing wastes could play a part in the future of biofuels. Fish processing wastes rich in fat may be used for biodiesel, although blending with other diesels may be necessary to meet biodiesel specification standards. Fish processing wastes are also suitable for biogas production, although these materials will have to be added as a co-substrate to boost the biogas production of plants treating agricultural or municipal wastes, due to the inhibitory effects of long chain fatty acids and high protein concentrations. A sustainable use of biogas in Norway would be as fuel for vehicles, as is the preferred future utilization in neighboring Sweden. In other countries with better developed gas grids, an increasing proportion of biogas will likely be used for grid injection to replace natural gas.

The increasing demand for energy, finite reserves of fossil fuels and concern regarding pollution and GHG emissions has led to intensive study of alternative fuels in recent years [1]. Fossil fuels comprise 80% of global primary energy consumed and 58% of this is in the transport sector [2]. Producing biofuels from organic waste products is of particular interest as waste materials can have a negative effect on the environment if incorrectly managed [3,4]. As more precise and adapted legislation regarding the management of organic wastes is developed, waste treatment systems are optimized in parallel [5].

When fuels derived from waste materials replace fossil fuels it is positive for the environment, as the waste products are renewable and carbon neutral [6]. Fuels from waste animal or vegetable oils and byproducts extracted during the refining of these oils are also considered to be environmentally superior to plant-based biofuels as they require no use of cultivated land [7]. A study of GHG balances of transport biofuels has shown that the use of rape to produce biodiesel has a GHG emission of more than 90 kg CO_2-e GJ^{-1}, greater than fossil petrol or diesel fuels [8]. The same study suggested biogas production from food wastes had the lowest emissions (approximately 10 kg CO_2-e GJ^{-1}), although biodiesel production from waste materials was not considered. Biomethane (gas of biological origin consisting of > 97% methane [9]) used to fuel buses has been shown to reduce NOx and particulate matter by at least 77% when compared with pre 2005 standard diesel buses, reducing pollutants in the immediate area [10]. Furthermore, using biomethane reduced CO_2 emissions by 63% when compared with compressed natural gas [10].

The aim of this paper is to examine the potential of **fish processing waste** for liquid and gaseous biofuels, and make a rough estimate about the amounts of biofuels that may be produced from this waste resource in Norway, a country with a significant fishing industry.

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Key terms

Fish processing waste: Includes silage prepared using dead fish (e.g., disposed due to illness), and guts and cuttings from both wild and farmed fish. Many of these wastes are currently used for a variety of purposes and hence available for energy feedstock only in limited quantities.

Stearin: Pure fish fat of relatively high melting point, extracted during refining of fish oils.

Bleaching earth: Bentonite clay, often with 10% activated carbon, containing residual fat, protein, vitamins, coloring and other substances derived from fish oil during refining, when clay and oil is mixed, heated and separated.

Soapstock: Fat extracted by alkaline aqueous solutions during refining of fish oils.

Category 2 waste: Animal waste products including manure and digestive tract materials, animal parts containing residual veterinary drugs, and animals that die except by slaughter for human consumption. The handling of such waste was first legislated by the European Union in 2002. Category 2 fish waste may be used for biogas digestion after heating at 133°C for 20 min at a pressure of 3 bar.

▪ The fish industry in Norway & globally

The fish industry is important in Norway. In 2009, 2.5 million tonnes of wild fish (round weight) were caught and nearly 850,000 tonnes of farmed fish were raised [101]. This comprises approximately 2.8% of the global fish harvest, which was 89.7 million tonnes in 2008, and 1.6% of the global amount of farmed fish, which was 52.5 million tonnes in 2005 [102]. Approximately 25% of the round fish is cut off as waste (e.g., heads and entrails) [103] but much of this waste (~75%) is utilized as resources, for example, as feed for the farmed fish. Significant amounts of fish and fish waste are also dumped at sea, and re-enters the marine ecosystem. The utilization of such material is not further discussed here.

Although the quantity of sea fish caught in Norwegian waters has remained fairly constant in recent years [101], on a global scale fish consumption is increasing rapidly; according to the Food and Agriculture Organization, the world average supply of fish grew from 9.0 kg per capita in 1961 to 17.1 kg per capita in 2007 [104]. However, the growth in consumption can be attributed to the developing world, whereas the consumption per capita in the developed world is decreasing slowly [1]. The fish industry also makes a significant contribution to GDP in other countries such as Sweden, China, Thailand and India [11] and it has been estimated that 74% of caught and farmed fish is used for human consumption [3].

▪ A country of oil & hydropower

In 2008, Norway was the sixth largest oil exporting country, with approximately 2.2 million barrels exported per day [101]. Norway is also an exporter of electrical energy; total electrical power production in 2008 was 142,667 GWh, of which 98.5% was from hydropower, whereas gross electrical consumption was 128,790 GWh [105].

Hydroelectric power in Norway expanded rapidly from 1960–1990 [12], although during the last 20 years there has been more focus on preservation of the natural environment. However, it has been estimated that Norwegian hydropower can be increased by almost a third without compromising environmental considerations too much [13]. Norway also has the possibility of generating a large amount of wind, wave and tidal electric power along the coastline, further increasing the renewable electricity production [14]. Agriculture is a less significant sector in Norway; approximately half the food consumed in this country is imported and only 4% of the land is cultivated. In addition to the large availability of hydroelectric power, this has contributed to a low interest in biofuels in Norway as compared with, for example, in neighboring Sweden.

Energy conversion from fish waste

The possibilities of producing energy from fish and fish oil waste products have been divided into three suitable technologies as outlined below.

▪ Direct combustion of fish processing waste

Oil products from the fish industry are suitable for direct combustion in furnaces or boilers, either for heat or combined heat and power (CHP) generation [15]. Fish **stearin** and ethyl esters from distillation of Omega 3 oils are commonly replacing mineral oils for incineration in fish oil industry plants in Norway today. Even fish silage [16] and **bleaching earth** [106] may be burned, but this is currently not a normal practice in Norway.

▪ Conversion of fish processing waste to liquid vehicle fuels

Raw fish oil has been found to be suitable as a fuel for internal combustion engines, although emissions of NOx, CO and engine smoke were inferior to an ester fuel manufactured from the same fish oil [17]. A major problem with fish oils as a direct fuel for internal combustion engines is that the oils are often of a high viscosity, which can lead to pumping and spray problems and the build up of carbon deposits [6,18]. The viscosity of fish oil is 11–17-times greater than diesel oil [6]; therefore it has been recommended that conversion to biodiesel to reduce viscosity is preferable [18]. Biodiesel is a mono-alkyl ester of fatty acids, conventionally created by reacting triglycerides in the oil with alcohol [7,19], although the costs of the emulsification and transesterification processes required add considerably to the cost [15]. Biodiesel has the advantage that it is miscible with mineral diesel [20] and therefore has limited requirements for changes in infrastructure. Biodiesel can also be directly utilized by vehicles with diesel engines. Fish silage is probably too low in fat to be a good substrate for biodiesel production, and bleaching earth is also likely too expensive to refine to this type of energy carrier. However, fish oil **soapstock** may be of interest here. A study with soy oil and soy soapstock showed that it was possible and even approximately 25% cheaper to produce biodiesel from soapstock produced during the refining of soy oil than from the soy oil itself [21]. Fish stearin and fish ethyl ester would probably be suitable for biodiesel production, but as previously mentioned, the industry currently makes good use of it so the price would have to be well above the price of mineral oil to be of interest for the fish oil industry to purchase. Diesel-like fuels (and lighter oils and gases) can also be obtained from animal fats by pyrolysis [22,23], typically at temperatures of 573–973 K [24]. The resulting heavy oil fraction distilled from waste fish oil pyrolysis has been found to be chemically similar to fossil diesel oil [25]. The syngas produced during pyrolysis of waste materials can also be used as a feedstock for Fischer–Tropsch synthesis for production of liquid transport fuels [26]. The Fischer–Tropsch process is a key technology for the creation of synthetic crude oil by the gas to liquid, coal to liquid [27] and biomass to liquid processes [28].

Conversion of fish processing waste to gaseous fuels

Anaerobic digestion is a widely used method for converting organic material to gaseous fuel. The resulting biogas consists of between 50 to 71% methane and 29 to 50% CO_2, with the higher methane concentrations available from the digestion of proteins and fats [29]. Although biogas produced at dedicated plants is a well-established technology (there are currently approximately 6000 biogas plants in Germany), biogas plants are not common in Norway. Data from a report of the Norwegian biogas potential claims that 300 GWh of biogas energy is already collected from landfill sites, of which 61% is used for electricity or heat, and that a further 180 GWh is produced by dedicated biogas plants [107]. The full potential of Norwegian biogas has been estimated at 6 TWh per year, of which 42% would be from animal manures, 23% from industrial wastes and 16% from households and small businesses [107].

The production of biogas from fish waste is possible for fish silage, cuttings/guts and the various fish oil byproducts, as practically any organic material is a potential substrate for biogas. However, fish processing wastes should be added to biogas plants with other materials as part of a co-digestion strategy. This is because fish processing wastes are often high in protein or fat content so co-digestion is necessary to avoid ammonia toxification of the methane producing bacteria or inhibition by long chain fatty acids (LCFAs), respectively. Biogas production is unlikely to exceed the demand for natural gas in any country [108] so it can only be part of the solution to renewable energy, but just as biogas is flexible in terms of the feedstocks required for its production, it is also very flexible in terms of its end use. Biogas is suitable for use at the biogas plant for electricity or CHP production, with very little processing or for further refining, before being injected into the gas grid system (where such infrastructure exists) or used as a vehicle fuel. Biogas as a vehicle fuel has some disadvantages when compared with biodiesel. In particular, the requirement for specialized fuelling stations, gas compression and the modification of vehicles for gas storage and engine fuelling are major barriers, but cheaper technology may be on the way: in Sweden, the inventor of the 'Biosling' pump to clean off CO_2 from the biogas was named inventor of the year in 2010 [109].

Fish waste materials available for bioenergy purpose

In Norway, fish processing wastes are available as a source of renewable energy, not only from the fish industry but also from fish farming (fish silage and fish manure from closed farming systems) and from the fish oil industry, which imports a large share of its raw materials and produces feed, for example, for farmed fish, and Omega 3 and cod-liver oils for human (medical) consumption.

From the fish harvest, 71,000 tonnes of cod-like fish (comprising several 'white' fish with low fat content as compared with herring and mackerel) were dumped close to or on shore in 2009 [110]. This comprises guts, heads, backbones and rudder fins. All similar waste from oily fish (herring and mackerel) is already commercially utilized, and hence not further discussed here.

From farmed fish (mainly salmon and sea trout), 51,000 tonnes of silage made from dead fish (dead or slaughtered as a result of sickness) was available in 2009 [110]. This waste is considered a **Category 2 waste** by the EU [111]. Category 2 wastes can be treated by a variety of methods, the most relevant to this study being incineration or transformation in a biogas plant or, specifically for fish wastes, ensiled [111]. Currently, most of the ensilaged Category 2 farmed fish from Norway is exported to Denmark to be used in biogas plants, after some oil is removed and used for energy purposes in the plants collecting the dead fish.

Byproducts rich in fat from the marine oil industry comprise four main groups **(Figure 1)** [Øyvind Sagli, Pers. Comm.], resembling different stages of oil refining. The first step is neutralization, where unstable fatty acids are removed by alkaline solutions, resulting in fish soapstock. The second step is bleaching of the oils by bleaching earth (acidulated calcium montmorillonite clay, occasionally with activated carbon addition for removal of polynuclear aromatic hydrocarbons [30]). This gives a residue rich in fat, and 3–5% (w/w) of bleaching earth powder is consumed during purification [Øyvind Sagli, Pers. Comm.]. The third step is winterization, to remove further unstable fatty acids such as stearin in a filtering process, with no chemical compounds added. The fourth step is a

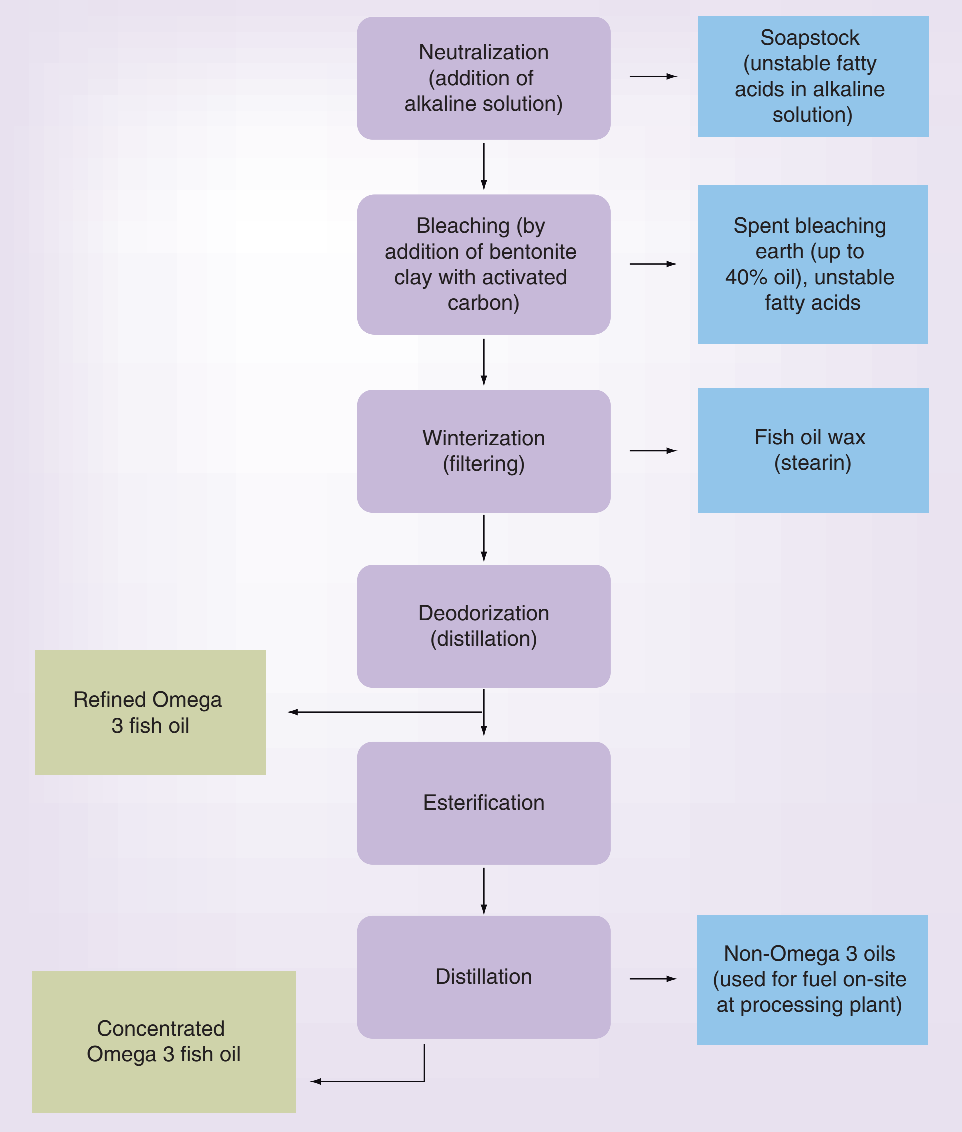

Figure 1. Stages of fish oil refining and four groups of processing wastes.

distillation to extract the valuable Omega 3 fatty acids for medical human consumption. About 28% of fish oil used for this production is 'harvested' as docosahexaenoic acid and eicosapentaenoic acid, which together constitute the Omega 3. The next step is esterification to fatty acid ethyl esters, which are currently utilized as a fuel for combustion at the Omega 3-producing plants, replacing fossil fuels [Ivar Storrø, Pers. Comm.]. A final distillation produces concentrated Omega 3 fish oils.

The stearin and ester fractions of the fish oil waste are easy to utilize as fuels for combustion, but are also likely of high interest for biodiesel production. If the price of biodiesel increases in the future, biodiesel could be an interesting option for this kind of fish waste. Fish oil soap and bleaching earth are currently not commercially utilized in Norway, and hence may be considered for bioenergy purposes.

Already in much of Europe, the increased interest in energy from waste has seen materials that were formerly expensive to dispose of becoming valuable commodities. For example, in Denmark, bleaching earth from the food oil industry was available for biogas plants, which were paid €30–35 per tonne to get rid of it 20 years ago. Today, the plants have to pay approximately that price to get hold of it [31].

When the bioenergy sector becomes more developed in Norway, it is likely that the price of waste materials will increase there too.

With increasing demand for animal proteins and increasing world populations, we will likely see an increased competition between the food and the food waste industry. People sold dried mice along the roadsides during the Malawi famine years. Why then drop cod heads in the ocean? How can we make new products for human and animal consumption from fish cuttings and leftovers? A direct competitor to the bioenergy industry in the fish waste market is the animal feed industry, including fish farming, and such competition tends to increase the price of waste products, thus reducing the financial feasibility of bioenergy production. Significant research and development efforts are conducted to invent new products and increase the utilization of fish byproducts for human and animal consumption. This point may decrease the availability of fish waste for energy purposes in future; on the other hand, fish processing wastes suitable for energy production are an intrinsic part of the production of, for example, marine oils for human consumption, which will likely increase in future as a consequence of increased interest in health and functional foods.

Economic considerations

▪ Bioenergy for transport

The high potential for Norwegian electricity production from nonbiomass renewable energy sources would suggest that the best possible use for liquid and gaseous biofuels would be in the transport sector, as was also the conclusion in a recent Swedish national study [112]. Due to the still very few biogas plants in Norway, the support for biogas as a vehicle fuel is not yet present in Norway, but some larger cities have started to use natural gas as a fuel for city buses, preparing for possible biomethane fuel utilization in future. A recent Norwegian study proposed that ten to 15 centralized biogas plants spread around Norway, digesting household and industrial waste, sewage sludge and animal manure and utilizing the gas to replace fossil fuels in vehicles would be beneficial from an economic and environmental perspective [113].

Support for bioenergy: Renewable Energy Certificates

In September 2009, Norway and Sweden signed a bilateral agreement to develop a common market for Renewable Energy Certificates (RECS) [114] by 1 January 2012 [115]. Such a system has been functioning and supporting the establishment of renewable energy plants in Sweden since 2003. Each country is obliged to fund the establishment of at least 13.2 TWh of renewable energy (hydro, wind or bio power) between 2012 and 2020, via RECS. This amount comprises approximately 10% of the current energy consumption in these countries. For 15 years, producers of renewable energy will receive one certificate per MWh electricity produced [114]. Electricity distributors have to buy the certificates along with the energy, and the costs will be distributed to the final energy consumers. The agreement aims at a stable increase in the production of renewable energy, so that the distributors have to increase their purchase of certificates by about 1.5 TWh annually; this is the reason for the increase in extra costs for the final consumer. This system will only impact the part of biogas production that is utilized for production of electricity, and will not impact the economy of a future biodiesel production in Norway. The largest effect of the RECS in Norway is expected to be promotion of small hydropower plants and windmills; whereas, in Sweden, wind power and combustion of renewable resources is expected to be supported.

Economic incentives for biodiesel production

Since 1991, producers and consumers of fossil fuels in Norway have to pay a CO_2 tax aimed at reducing the emissions of GHGs. For 2011, this tax comprised 11.15 € cents per liter gasoline and 7.5 cents per liter mineral diesel [116]. A tax waiver is available for biodiesel. A further and more significant tax related to fuels, however is the road charge. The aim of this tax is that people using Norwegian roads shall pay for the costs related to establish and maintain the roads, and further for costs posed on society due to, for example, environmental pollution and accidents. The tax is charged per liter of fuel, and comprises (in 2011) approximately 58 cents for gasoline, dependent on the content of sulfur. For mineral diesel it comprises approximately 46 cents per liter dependent on sulfur content, and for biodiesel 23 cents [114].

In 1998–1999, there were hard discussions about the taxing of biodiesel in Norway. Facilitated by lobbying from NGOs, the Ministry of Finance proposed to remove the road tax for biodiesel, not only when sold as pure biodiesel but also when mixed with mineral diesel. A total of €44 million were invested in the Uniol biodiesel production plant, with a production capacity of 100,000 tonnes per year, and production started in 2008. A few months later, the road charge was set to half the level of mineral diesel from 2010. To support biodiesel, the government aims at mixing 5% biodiesel into all mineral diesels. By 2011, the mixing rate is still only 3.5%. Considering the biodiesel used in Norway today is imported and primarily produced from rape seed oil, it is currently questioned whether biodiesel is really sustainable due to the competition between energy and food crops for land, water and nutrients. The production of biodiesel at Uniol closed down in 2009, but the plant has recently been bought by a foreign company and started to produce biodiesel again by January 2011.

Economic incentives for biogas production

Biogas in many European countries such as Denmark and Germany is most commonly used for the generation of electricity or CHP where a heat demand is available. Biogas used for electricity production in Denmark has a guaranteed sale price of €0.1 per kWh_{el}, whereas no such subsidy is available if biogas is used for vehicle fuel or grid injection. In Germany, using biogas for CHP is favored due to the Renewable Energy Resource Act with maximum feed-in tariffs of nearly 28 cents per kWh_{el} guaranteed for 20 years [32]. A comparable financial support for biogas production is not found in Norway or Sweden, and in Norway the traditionally low prices on electricity seriously hamper the establishment of all bioenergy production.

Currently in Sweden, as much as 10% of the biogas produced is used as a vehicle fuel because of incentives including exemption from fossil fuel CO_2 tax (also for CHP utilization) and congestion charge in Stockholm, free parking in some cities, and subsidies for investment in bi-fuel cars in certain municipalities. The remaining 90% is mainly going to CHP production [33]. Similar support schemes have not yet been developed in Norway due to the low availability of biogas, but investments in biogas plants may receive a public support of up to 40% of the costs for farm-based plants, and 30% for larger plants (above 1 GW_{el}).

As shown, the development of the bioenergy sector in Norway is rather incoherent, and energy production from fish processing waste must adapt to frame conditions of seemingly large uncertainty.

Key term

Organic pollutants: Chemical residues that have the potential to accumulate in marine species, for example, organochlorine pesticides such as DDT, dioxins, polychlorinated biphenyls and brominated flame retardants.

Technical & structural barriers to biodiesel & biogas production from fish processing wastes

Biogas upgrading & transport for vehicle fuel application

The use of biogas as a vehicle fuel or replacing natural gas in gas grids requires upgrading to biomethane to ensure a consistent fuel of high calorific value. The CO_2 in the biogas needs to be removed to improve the calorific value and trace compounds, such as hydrogen sulfide and siloxanes (silicon oxide bonded to hydrogen atoms or a hydrocarbon group), need to be removed, as these can be damaging to equipment [34]. The use of biogas for electricity production or CHP requires scrubbing of hydrogen sulfide only and is most often achieved by biological methods on site [29]. With current technology, the cost of scrubbing biogas to natural gas or vehicle fuel standards and compressing it to a pressure where filling up the vehicle does not take too long, affects process economy considerably and, as is the case for biogas plants, there is considerable economy of scale [107]. It has been estimated that a typical treatment plant processing 300 m^3 of dry biogas at standard temperature and pressure per h has an investment cost of €1 million, and the combined capital and operational costs range from 1.2 to 1.4 cents per kWh of energy in the scrubbed gas [108]. However, new technologies to reduce the cost of biogas scrubbing, such as the previously mentioned Biosling system, are emerging. This system uses water in rotating coiled plastic hoses to absorb CO_2 from biogas at 2 bar pressure. The end product is a gas of 94% methane. Further upgrading to gas grid or vehicle fuel quality can be achieved by adding a water scrubbing column downstream of the Biosling system [117].

In many countries, such as Norway and Sweden, there are little significant gas grid networks and therefore the use of biomethane for vehicle fuel requires transport from production sites to the end user. In Germany, the costs of producing, cleaning and transporting biomethane for grid injection has been prohibitive for all but the larger scale biogas plants and as a vehicle fuel; even a removal of CO_2 tax and energy tax on biomethane has failed to make it competitively priced when compared with bioethanol or natural gas [32]. The requirement of an extensive fuel filling station infrastructure is another major barrier against the use of biomethane as a vehicle fuel. However, biomethane is suitable for fleet vehicles such as buses and delivery vehicles, which could use slow overnight filling stations at centralized facilities.

Biodiesel specifications

Biodiesel is subject to specification standards such as EN 14214 (European standard for fatty acid methyl ester biodiesels) and ASTM D 6751 (international standard for biodiesels blended with middle distillate fuels). A major obstacle for fish-waste derived biodiesel is the high concentration of polyunsaturated fatty acids. Both EN 14214 and ASTM D 6751 limit polyunsaturated fatty acid concentrations to a maximum of 1% [35,118] and these limits have been exceeded in biodiesels made from raw fish oil [35] and fish oil soapstock [7]. Polyunsaturated fatty acid concentration in fish oil biodiesel is proportional to its oxidation power [36]. Oxidation of biodiesel produces aldehydes, carboxylic acids, ketones and sludge composed of polymerized fatty acid methyl ester molecules [36], all of which is destructive to diesel engines. However, blending fish-oil derived biodiesel with used cooking oil biodiesel could result in a product satisfying the ASTM D 6751 [36].

Challenges linked to fish soapstock, bleaching earth & fish silage for biodiesel

Soapstock is extracted in large quantities during fish oil refining, estimated at 25% of the fishery production [37]. Soapstock contains many free fatty acids in an emulsion with water, which makes them difficult to extract and the water itself also inhibits the transesterification process [21]. Esterification of free fatty acids normally requires an acid-catalyzed reaction in addition to the usual alkali-catalyzed reaction, but the high concentration of water present also inhibits the acid-catalyzed reaction [21]. Alternative methods of producing biodiesel from soapstock include thermal cracking [38] and lipase enzyme-based methods [21].

Bleaching earth can be recycled enzymatically with lipases to remove practically all adsorbed organic molecules, the extracted fatty acid alkyl esters being suitable for biodiesel production and the mineral fraction re-used or sent to landfill [39]. However, the cost of using lipases for biodiesel production is a major obstacle that can be overcome by immobilization of the enzymes to reduce losses [40].

The fat fraction of fish silage may be used for biodiesel; however, this part already is utilized for incineration by the fish processing industry. If biodiesel prices increase significantly the use of fish oil for biodiesel may increase in the future.

Challenges for using soapstock, bleaching earth & fish silage for biogas

The use of fish waste in biogas reactors is not without difficulties; of particular importance are the high fat and/or protein content of fish processing wastes. Even if the whole fish waste is used for biogas production, including the fats, the protein content of fish waste can be as high as 74% of the dry matter [41] leading to high nitrogen and sulfur loads to the reactor and consequent inhibition by ammonia [42] or sulfide [43]. Ammonia inhibition of anaerobic processes is subject to acclimation but a typical threshold inhibitory concentration is about 4 g N l^{-1}, whereas the total nitrogen content of fish ensilage and wastes consisting of heads, tails, bones and viscera can be more than 33 g N kg^{-1} [44]. Moreover, fish waste materials are often rapidly degraded anaerobically [45] with the problem that precursors to methane can be formed faster than they can be metabolized and inhibitory levels can be reached. For example, oil feedstocks are digested to LCFA very rapidly, which can lead to LCFA accumulation and subsequent inhibition [43].

Table 1 shows measured parameters for bleaching earth, stearin and soapstock, kindly made available by the fish oil company GC Rieber, Norway [119]. As shown, soapstock is highly alkaline, with a pH of 9.8, due to sodium hydroxide used in its production. Biogas processes have been shown to be adversely affected by concentrations of sodium above 0.21 mol l^{-1} (4.83 g l^{-1}), a concentration considerably less than that found in soapstock **(Table 1)**.

Bleaching earth from the food oil industry has long been utilized in biogas plants [46]. Addition of bentonite clay to laboratory digesters decreased the inhibition that oil additions posed to the biogas production, indicating that not only the fat in the bleaching earth but also the clay minerals may be positive for a commercial digester [26]. Spent bleaching earth from oil processing industries is available in large amounts worldwide and contains up to 40% w/w oil [47]. Hence, these materials have the potential to increase the energy output significantly; however, the mineral particles will cause abrasive wear on mechanical equipment and form sediments in reactors and storage tanks.

A key to successful anaerobic digestion of many organic wastes is co-digestion with other materials such as manure [44,48], sewage sludge [49,50] or plant material [45]. Co-digestion with these materials can increase the buffering capacity of the feedstock and maintain the carbon to nitrogen ratio within the ideal range of 25–30:1 [51]. The methane yields of manures are low, in the region of 150–250 l CH_4 per kg volatile solids [48,52], but can be considerably increased by the addition of fish processing wastes [44,48]. Sewage sludge typically has a higher methane yield of 300–350 l CH_4 per kg volatile solids [53], but can still be subject to substantial yield increases upon the addition of waste materials [50].

Table 1. Examples of contents of heavy metals, minerals and total organic carbon, dry matter, pH value and fat content in various fish wastes.

Element	Bleaching earth	Fish stearin	Fish soapstock
pH	3.3	4.9	9.8
Dry matter (%)	96.0	99.0	28.7
Total organic carbon (mg/kg TS)	340,000	260,000	430,000
Fat (%)	13.2	61.5	21.1
Na (g/kg TS)	0.80	0.020	41
P (g/kg TS)	0.24	0.0030	0.84
K (g/kg TS)	1.1	0.0010	0.10
Mg (mg/kg TS)	4600	3.1	86
Ca (g/kg TS)	3.9	0.030	0.42
As (mg/kg TS)	20	<0.43	58
Pb (mg/kg TS)	6.4	<0.22	<0.91
Cd (mg/kg TS)	<0.042	<0.040	<0.17
Cu (mg/kg TS)	5.4	0.15	0.66
Cr (mg/kg TS)	4.5	0.040	<0.17
Hg (mg/kg TS)	0.0094	0.0081	0.010
Ni (mg/kg TS)	7.6	<0.13	<0.52
Zn (mg/kg TS)	15	1.1	5.9

TS: Total solids.
Data from [119].

Food safety issues

Fish, especially fatty species, are on top of nutrient chains and accumulate toxic compounds such as heavy metals and **organic pollutants**. Threshold values in biogas residues need to be defined to ensure that the digestate qualifies as a fertilizer for agricultural purpose, for example, with respect to the concentrations of heavy metals. Heavy metals have been found to be higher in fish wastes than in meat wastes, fruit and vegetable wastes, restaurant or household wastes [54]. This can be attributed to bioaccumulation via feeding and direct uptake through gills [55]. In a survey of ten European biogas plants, the highest concentrations of trace elements (mostly heavy metals) were found in digestate from biogas plants treating bleaching earth [56]. However, the addition of waste materials to biogas plants treating manure and energy crops can also be beneficial for the biogas process as trace elements (in suitable concentrations) are in many cases necessary for microbial function, and a constant addition via co-digestion ensures that these are not depleted over time [56]. Arsenic has a special interest since it is common in marine environments, and is enriched in fish fat. By production of fish oil for human consumption, arsenic is removed during neutralization and bleaching.

Random samples of bleaching earth contained 20 mg As kg^{-1} dry matter and soap contained as much as 58 mg As kg^{-1} dry matter. A random stearin sample contained less than 1 mg **(Table 1)**.

For organic pollutants (e.g., PCBs and DDT), chemical analyses confirm that these substances are found in the oil byproducts. However, as fish oil is a product where such substances may be removed, the threshold values for human consumption given by WHO and the EU are rather low [120]. Analyses of single substances are transformed to toxic equivalency factors according to a method established by the WHO. For the sum of dioxins/furans and dioxin-like PCBs, the limit for human consumption of marine oils is 10 pg per g fat (WHO PCDD/F-PCB-TEQ). For soapstock and bleaching earth analyzed in April 2011, this value was 59 and < 1 pg [Øyvind Sagli, Pers. Comm.] To illustrate the level of 10 pg, in flat fish and lobster, values of 150 pg or more may be found, but they are still consumed. Removing organic pollutants from these products would destroy them for food purposes. Care should be taken to keep soil concentrations below critical limits, but in general, the fish oil processing waste and byproducts do not seem to contain more harmful substances that are possible to cope with from a food safety point of view.

▪ Co-substrates of special interest by small-scaled farm structure

The size of farms logically affects the size of farm-scale digesters. A Swedish study of farm-scale biogas plants between 51 and 201 kW (continuous) energy production found that scale was a major parameter determining the financial feasibility [57], with larger plants costing less per kWh of energy produced. However, the study also found that increasing biogas production with the addition of high-yielding substrates significantly improved the financial feasibility [57]. Although the structure of production agriculture in Norway has changed considerably over the last 40 years, with an increase in the average farm size and a decrease in the number of farms, the number of large farms producing enough manure to justify the expense of building a biogas plant is still much less than in other countries such as Denmark and Sweden. The agricultural statistics can be compared as follows: in 1969, 57% of Norway's 155,000 farms were less than 5 ha, only 0.32% of farms were greater than 50 ha and average stock per holder was 10.6 cattle or five breeding pigs. By 2008, the number of farms had fallen to 48,800 with 12.8% below 5 ha, 6.6% greater than 50 ha and average stock was 48.2 cattle or 60.2 breeding pigs per holding [101]. In Denmark in 2009, 34.2% of farms were greater than 50 ha and only 3.7% less than 5 ha. The average stock per holder (in 2007) was 100.3 cattle or 1903.4 pigs [120]. Based on these stock figures, the methane productivities found by Møller *et al.* [52], and using a methane energy value of 10.83 kWh/m^3 CH_4, energy productivity for an average Norwegian cattle farm could be expected to have a total power output of only 166,000 kWh per year, whereas for an average Danish cattle farm the power output would be 345,000 kWh per year. The addition of oily waste materials such as stearin at just 5% w/w could quadruple the methane productivity of a biogas reactor normally operated on cattle manure [48]. For farms located nearby a fish industry, utilization of fish waste is an interesting option.

One option to increase the scale of biogas plants is the construction of centralized plants. These plants take in manure from a number of farms local to the plant and often add waste materials to boost biogas production [58]. However, the distance between the biogas plant and farms supplying manure and waste sources affects the economics considerably; the primary energy input to output ratio has been found to exceed 100% with transport distances greater than 22 km with cattle manure and greater than 80 km with food wastes [59]. Nearly 60% of Swedish biogas production is from waste water treatment rather than agriculture, with a further 30% from landfills [33]. This tends to position the plants within a reasonable distance of relatively large population centers. Norway is even less densely populated than Sweden, but animal husbandry is rather intensive in some regions. Centralized manure based biogas plants have been planned in some such places, but have so far not been economically feasible to establish as long as only investments are supported.

Integrated approach to maximize bioenergy recovery from fish processing waste

Preparing for a future of reduced supply of mineral oils, any natural or waste substance suited for diesel production will be of high interest, to be able to utilize the infrastructure already available and adapted to diesel fueling. Mixing the fish processing waste derived biodiesel with mineral diesels will produce a fuel that should conform to the specification standards EN 14214 and ASTM D 6751 [35], allow the Norwegian government to come closer to their target of 5% biodiesel mixed in all mineral diesels and be better for the environment than the existing imported rapeseed oil biodiesels [8].

The production of biodiesel has many byproducts. Raghareutai *et al.* have shown that for every 1 m^3 of biodiesel, byproducts consisting of 8 kg of bleaching earth, 140 kg of glycerol and 0.5 m^3 of wastewater with a chemical oxygen demand of up to 170,000 mgl^{-1} are produced [60]. These byproducts can be marketed to increase the financial feasibility of the process. Glycerol has many uses including plastics production, lubricants, foods and drugs [20] or can be used as a feedstock in anaerobic digestion [61]. Refining or recycling of the glycerol and anaerobic treatment (for biogas production) of the wastewater produced during biodiesel manufacture may be the optimal practices from an environmental perspective [60]. Spent bleaching earth from fish processing and biodiesel processing is also a substrate for anaerobic digestion, although recycling of the oil from bleaching earth by immobilized lipase enzymes could also be used to improve the biodiesel yield. A block diagram showing an integrated approach for conversion of available fish processing wastes to biodiesel and biogas is shown in **Figure 2**.

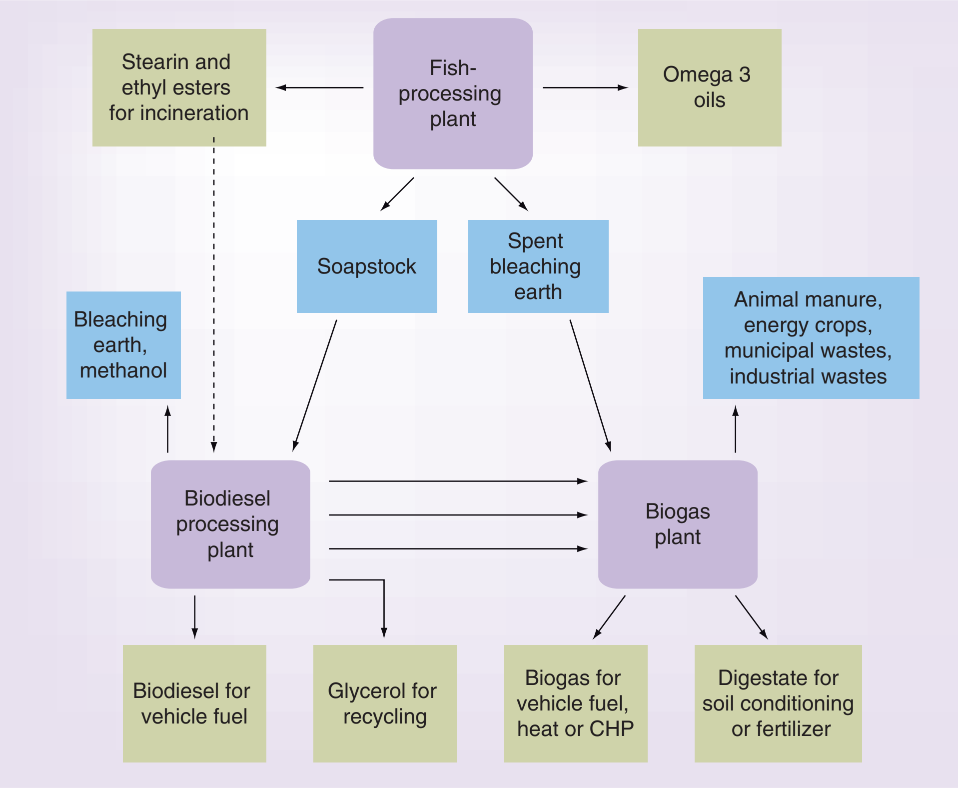

Figure 2. Integrated biodiesel and biogas processes using waste products from an Omega 3 oil processing plant to maximize the potential of fish processing wastes. The dotted arrow shows a future possibility of utilizing more oil-rich products for biodiesel production if a cheaper renewable alternative is found for on-site combustion.
CHP: Combined heat and power.

▪ Energy potentials from Norwegian fish processing wastes

Assessments of the available amounts of fish oil waste are difficult because several plants produce and refine fish oil, and information about waste amounts is sensitive. In 2010, 226,000 tonnes of marine oils and fats were imported for the production of marine oils [101]. A reasonable assessment could be that at least 20% of this amount should be available as waste in soap and fatty residues in bleaching earth, resulting in 45,000 tonnes of such material. For the further considerations in this paper, we have carefully estimated that 20,000 tonnes of fish oil soapstock and 30,000 tonnes of bleaching earth may be available annually from Norwegian fish oil industry for bioenergy purpose. It must be stressed that the following analyses are only estimations of production, so we believe it best to maintain a simplistic approach.

Calculating energy production is also difficult. Andersen and Weinbach have previously used conversion estimation that 1 t of oil produces 0.95 t of biodiesel to calculate total potential fish processing waste derived biodiesel in Norway [62].

A calculation of the methane potential of organic materials can be made using the formulae first described by Buswell [63]. The Buswell formulae can be used to calculate the theoretical biogas and methane potentials of substrates based on their chemical formulae, for this calculation average chemical compositions of fats and proteins have been used as described by Ward [48]. The Buswell formula for calculating the theoretical biogas potential based on C, H and O composition is shown in **Equation 1**:

$$C_aH_bO_c + \left(a-\frac{b}{4}-\frac{c}{2}\right)H_2O \rightarrow \left(\frac{a}{2}+\frac{b}{8}-\frac{c}{4}\right)CH_4 + \left(\frac{a}{2}-\frac{b}{8}+\frac{c}{4}\right)CO_2$$

Equation 1

Often, the Buswell formulae overestimate the actual gas potentials [52], in this case an estimate that 60% of the protein and 80% of the oil are converted to biogas under anaerobic conditions.

The methane yield of the wastewater from biodiesel production can be estimated at 140 ml CH_4 per g COD [64].

▪ Integrated biodiesel & biogas production

Considering the integrated approach outlined in **Figure 2**, the following calculations can be made: if the 95% conversion estimation [62] is applied to the available 20,000 tonnes of soapstock (with a composition of 21.1% oil, **Table 1**) an additional 4.0 kt of biodiesel could be produced. This is approximately 51.8 GWh total energy.

Utilizing the bleaching earth from fish processing as a co-substrate for anaerobic digestion (Figure 2), estimated at 30 kt per year with an oil content of 13.2% (Table 1), could produce an extra 1.5 million m^3 of methane (16 GWh total energy) when used as a co-substrate in biogas plants.

The wastewater produced during biodiesel processing has been estimated at 85 kg COD per cubic meter of biodiesel produced [61]. Converting volume to mass using an average density of 0.88 kgl^{-1} [65] gives 74.8 kg COD per ton of biodiesel. which equates to 10.47 m^3 methane from the wastewater produced per ton of biodiesel. Using the estimate of 4 kt of biodiesel from soapstock calculated above would give approximately 42,000 m^3 of methane with an energy potential of 454 MWh. Bleaching earth from the production of soapstock biodiesel could also be used for biogas but the quantity is very small.

From the integrated approach outlined above the biodiesel potential of soapstock is only 0.4% of the 13,184 GWh consumed as gasoline by private vehicles alone in Norway in 2008 [101]. Adding the biogas potentials of wastewater and bleaching earth slightly increases this to 0.52%. Diesel passenger cars in Norway constitute around 23% of the total number [66]; clearly the energy contribution from fish processing waste derived biodiesel falls some way short of the 5% addition of biodiesel to all mineral diesels proposed by the Norwegian government.

If fish processing waste biofuels were used for agricultural purposes, estimation can be made as follows: an 80 horsepower tractor uses 16.3 l (14.3 kg) of diesel to plough 1 ha [67]. If all the soapstock fish processing waste in Norway was converted to biodiesel, this would be sufficient diesel to plough 280,000 ha. In 2009 the total agricultural area of Norway was 1.02 million ha [101].

▪ Additional biogas production using Category 2 wastes as a co-substrate

Below are calculated the yearly methane productivity values and the respective total energy productions in GWh from Category 2 fish processing wastes. It must be stressed that these values represent the fish processing waste contribution to the total biogas production as part of a co-digestion strategy.

From Equation 1 and the estimates of anaerobic conversion, Category 2 fish waste from aquaculture (estimated at 51 kt per year [110], 45% oil and 45% protein) used as a co-substrate in biogas plants can be estimated to produce an additional 18.6 and 9.0 million m^3 of methane from the oil and protein fractions respectively. This is equivalent to a total energy of 298 GWh based on 10.83 kWh/m^3 CH_4). Much of this material is currently exported to Danish biogas plants. As Danish biogas plants produce biogas for CHP purposes only, an estimation of electricity production can be made (using the mean electrical conversion efficiency of 40.6% reported by Walla and Schneeberger for large scale CHP units [68]) of 121 GWh_{el} to the electrical grid every year. This could power more than 7500 homes, based on a 16,000 kWh_{el} average yearly electrical consumption calculated from data supplied by Statistics Norway [101].

Future perspective

The use of fish processing wastes for energy should not take precedence over production of food, animal feeds or cosmetics, particularly where these uses place a higher value on fish wastes.

Hence, we propose that all oil fractions from fish processing waste (soap stock, stearin, ethyl esters) should be prioritized for biodiesel production. Incineration for heating, for example, in the fish processing industry, should be replaced by other biological material of a lower calorific quality, such as wood. Biomethane should preferably be used for powering tractors in agriculture, and buses and delivery vehicles in cities. These vehicles are well suited to biomethane as a fuel as they tend to have limited range and will return to a centralized depot when not in service where gas storage and pumps may be available for slow, energy efficient refueling.

In other countries a similar scenario is predicted but with a continuation of the current trend for CHP production from biogas (due to economic incentives) although we believe that more and more biogas will be upgraded to biomethane for vehicle or gas grid use. Upgrading of biogas to natural gas or vehicle fuel quality will become cheaper as new technologies emerge.

For biogas production, fish wastes can be used as a co-substrate with agricultural wastes (typically manures) or sewage sludges for increased productivity and profitability of biogas plants whilst maintaining process stability.

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Executive summary

Fish consumption & waste treatment

- World fish consumption is growing in developing countries, leading to larger quantities of fish processing wastes.
- Increasing demands for energy coupled with more stringent requirements for waste treatments make fish processing wastes ideal candidates for biofuel production.
- Fish processing wastes have a great potential for energy production but should first be considered for animal feed or other nonfuel uses where possible.

Conversion of fish processing wastes to biofuels

- Fish processing wastes are flexible in terms of the types of biofuels that can be produced, for example, biodiesel, bio-oil, biogas or direct combustion of oil-rich wastes.
- Many fish processing wastes are already used as biofuels, for example, stearin, an oil-rich byproduct filtered from fish oil during refining and used to fuel the fish processing plant.

Economic considerations

- Current renewable energy support in some countries such as Norway, Germany and Denmark is focused on the production of electricity.
- Biodiesel in Norway is subject to a CO_2 tax but at half the rate of mineral diesel and the Norwegian government aims to mix 5% biodiesel with all mineral diesels.
- The large potential of hydroelectric power in Norway means biofuels are expected to be used for transport purposes in the future, as is the case with Sweden.

Technical & structural barriers

- Biodiesel from fish processing wastes is unlikely to conform to specification standards but this can be avoided by blending with other biodiesels or mineral diesel.
- Fish processing wastes such as soapstock require more complex processing for biodiesel production than is necessary for clean oils.
- The high protein and/or oil concentrations in fish processing wastes can lead to inhibition of biogas processes, therefore these wastes should be used as a co-substrate with other materials.
- To use biogas as a vehicle fuel requires extensive upgrading, which can add considerably to the cost.
- Fish wastes may contain heavy metals and organic pollutants, which need to be considered to ensure that the digestate from biogas plants qualifies as fertilizer or soil conditioner.

Integrated approach

- Using soapstock for biodiesel production, and bleaching earth and biodiesel waste products for biogas production, is a sensible use of currently available wastes.
- Using wood or other plant biomass for combustion at fish processing plants will allow stearin and ethyl ester products currently used for this purpose to be channeled into transport biofuel production.

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