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A case of circular economy iA Case of Circular Economy in the Norwegian Aquaculture Sector

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Master of Science in Safety, Health and Environment
Submission date: July 2023
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Abstract

As the global demand for protein is increasing, the aquaculture industry have become significant factor in meeting this demand and is in turn growing to be one of Norway's biggest industries. The speed of development, along with the growing environmental challenges, gives both potential and need for a sustainable development within the sector.

This thesis takes a look at the current status of circularity in the Norwegian aquaculture sector, and along with company visits and material science identify knowledge gaps and challenges moving forward. Pyrolysis-Gas Chromatography/Mass Spectrometry (Py-GC/MS) was used to analyse the polymers and look for chemical changes during the recycling process.

In addition to the observed density changes and reduces Material Flow Rate (MFR), a loss of additives during recycling was observed. Knowledge gaps make further work necessary to determine the effects and how to reverse them. Overall, a higher integration of interdisciplinary material sciences could help close gaps and increase circularity, as current practices focus mainly on physical properties.

Keywords: Circular economy; Plastic recycling; Waste management; Material composition; Py-GC/MS; Aquaculture;

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First and foremost, I would like to thank my supervisor, Associate Professor Paritosh Deshpande for excellent support, encouragement and belief during the project work. I am grateful for all the inspiration and constructive feedback, which have helped shape the thesis.

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Furthermore, I would like to thank my classmates and friends - on and off campus - for the last two years of fun, social activities and good conversations during this degree.

Contents

List of abbreviations

CE	Circular Economy
EOL	End-of-Life
EU	European Union
FTIR	Fourier-Transform Infrared Spectroscopy
HDPE	High-density Polyethylene
LDPE	Low-density Polyethylene
MFR	Material Flow Rate
PAC	Plastic Associated Chemical
PE	Polyethylene
PP	Polypropylene
PVC	Polyvinyl Chloride
Py-GC/MS	Pyrolysis–Gas Chromatography/Mass Spectrometry
SDGs	Sustainable Development Goals
SSB	Statistics Norway (Norwegian: Statistisk Sentralbyrå)
TD-Py-GC/MS	Thermal Desorption - Pyrolysis–Gas Chromatography/Mass Spectrometry
UNEP	United Nations Environmental Programme

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1 Introduction

In the face of mounting environmental challenges and growing concerns over resource depletion, the concept of a circular economy (CE) is gaining traction among scholars and practitioner (Kirchherr et al. 2017, 2023). Simultaneously, the international community has recognised the urgency for a coordinated global effort to address the complex issues of climate change and environmental degradation. The United Nation have used the Sustainable Development Goals (SDGs) to set a shared vision for a sustainable development.

United Nations Environmental Programme (UNEP) further specifies a circular economy as one of the sustainable business models. Results from Garcia-Saravia Ortiz-de-Montellano et al. (2023) suggests that ”CE strategies can contribute to all SDGs, but most effectively to SDGs 8 – decent work and economic growth, 12 – responsible consumption and production, and 13 – climate action.” Thus, by integrating the principles of a circular economy into various sectors, we can make significant strides towards achieving the SDGs and foster a more sustainable planet.

1.1 Circular economy in Norway

Overall, Norway currently have a quite linear business model. However, according to de Wit et al. (2020), Norway can go from 2,4% circularity to 45,8% by restructuring Norwegian industry (circularity here defined as the share of cycled materials in total material inputs into the national economy every year).
For durable plastics, an even higher circularity is within reach. According to Systemiq et al. (2023*a*), circularity levels of over 70% can be achieved, whilst reducing greenhouse gas emissions by 90% (Systemiq et al. 2023*b*).

As the global demand for protein is increasing, the aquaculture industry have become significant factor in meeting this demand and is in turn growing to be one of Norway’s biggest industries. In 2020, Norway alone produced 1,5 million tonnes of aquatic organisms, compared to 1,1 million for the EU. This made Norway the seventh largest producer in the world, and the second largest exporter, after China (Eurostat 2022). With the big increase in demand for sustainable marine protein, aquaculture is one of the fastest growing sectors of Norwegian industry. Production is projected to expand to 5 million tonnes by 2050 (Solberg et al. 2021). The high speed of development within the sector implies a need for scientific input to keep up with the development, in order to insure a sustainable industry in the future.

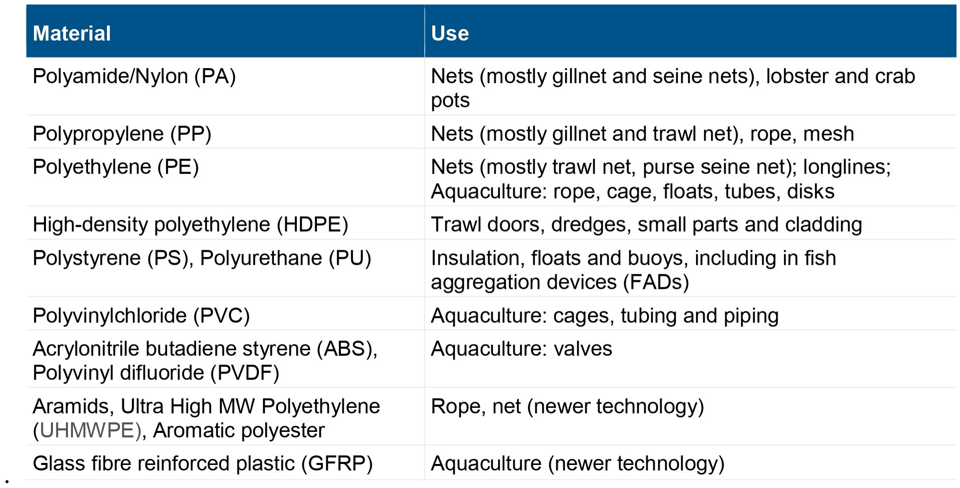
The aquaculture industry has an impact on most SDGs, mainly and most directly those related to zero hunger (SDG 2) and environmental sustainability for oceans, land, and climate through responsible production patterns (SDG 12, 13, 14, and 15) (Troell et al. 2023).

SDG 12 further states reduction in waste generation through prevention, reduction, recycling and reuse as one of the target goals (SDG target goal 12.5). This aligns with the purpose of CE, and principles of CE are considered essential measures to mitigate and ensure the sustainable management of plastic waste in the EU (Deshpande et al. 2020). We know that plastic wastes have caused undeniable sustainability impacts at a multi-nation scale (Loy et al. 2023), and Garcia-Saravia Ortiz-de-Montellano et al. (2023) shows how "clean and effective end-of-life (EOL) for products" is proven to be one of the most influential contributions to the SDGs.

1.2 Aquaculture gear and waste flow

Plastic is the most commonly used material in aquaculture, accounting for 73% of the weight of material used (Systemiq et al. 2023*a*). There are many different plastic polymers that are common in aquaculture, some shown in Table 1, with variations of polyethylene (PE) being the most common polymer (Systemiq et al. 2023*a*). The producer in this study uses high-density polyethylene (HDPE) which is a commonly recycled material (Vildåsen 2019). HDPE is, amongst other things, also used in floats for cages, twines and ropes, pipes and more, with the local producer producing walkways and brackets from HDPE. It is more commonly recycled than for example polyvinyl chloride (PVC) or low-density polyethylene (LDPE). (Huntington 2019)

Table 1: *Overview of plastic types used in fishing and aquaculture gear. Source: Commission & for Environment (2018)*



Material	Use
Polyamide/Nylon (PA)	Nets (mostly gillnet and seine nets), lobster and crab pots
Polypropylene (PP)	Nets (mostly gillnet and trawl net), rope, mesh
Polyethylene (PE)	Nets (mostly trawl net, purse seine net); longlines; Aquaculture: rope, cage, floats, tubes, disks
High-density polyethylene (HDPE)	Trawl doors, dredges, small parts and cladding
Polystyrene (PS), Polyurethane (PU)	Insulation, floats and buoys, including in fish aggregation devices (FADs)
Polyvinylchloride (PVC)	Aquaculture: cages, tubing and piping
Acrylonitrile butadiene styrene (ABS), Polyvinyl difluoride (PVDF)	Aquaculture: valves
Aramids, Ultra High MW Polyethylene (UHMWPE), Aromatic polyester	Rope, net (newer technology)
Glass fibre reinforced plastic (GFRP)	Aquaculture (newer technology)

Although neither the aquaculture sector nor Statistics Norway (SSB) maintain comprehensive statistics on (plastic) waste generated, several estimates have been made. Sundt et al. (2014) estimated annual plastic waste flow in the Norwegian aquaculture industry to be 13 300 metric tonnes in 2011, with only 21% being recycled (Huntington 2019). According to Hognes & Skaar (2017), this annual is somewhere between 16 000 - 29 000 tonnes (low/high-estimates), with 29 000 tonnes corresponding to 14% of total annual plastic waste in Norway. Sundt et al. (2018) estimated the plastic waste flow to be 25 000 tonnes.

For aquaculture in the EU in 2015, there was 15 295 tonnes of plastic aquaculture gear entering formal waste management every year, with loss to the environment estimated at 15% overall for all gear and sectors (Commission & for Environment 2018).

1.3 Research objectives

These numbers and estimates illustrate the size of the Norwegian aquaculture industry, further stating the importance of proper waste management and circularity in Norwegian aquaculture. A higher circularity for plastics in Norwegian aquaculture is not only desirable, but also an achievable step. An analysis by Systemiq et al. (2023*a*) shows that ”the demand for virgin plastics in fisheries and aquaculture can be reduced by 16,000 tonnes (48%), and the sector shift from 35% to 81% circularity by 2040.” (Circularity in this report defined as 'a % of annual demand for plastic utility corrected for net addition to stock')

Therefore, this thesis will explore the actions and principles behind the term "circular economy", and use this as a foundation to create a picture for better understanding the barriers, challenges and future work needed to achieve higher circularity of plastics in the Norwegian aquaculture industry. By chemically analysing the polymers, the aim is to also identify knowledge gaps in the material science behind the recycling process.

To do this, the thesis will answer the following research questions:

- What are the current practices in realising a higher circularity for plastic polymers from Norwegian aquaculture sector?
- Are material properties of virgin and recycled polymers included in the determining circular economy strategies for plastics from the Norwegian aquaculture sector?
- What are the knowledge gaps of plastic associated chemicals in realising circularity for end-of-life-plastics from the aquaculture sector?

1.4 Scope

The scope of this thesis is limited to plastic gear within Norwegian aquaculture sector, with a focus on waste from plastic gear. A local plastic product producer, which produces parts for aquaculture farms, and a local waste management company serve as the case companies for this study. Since HDPE is the main polymer in their operations related to aquaculture industry, the material challenges will focus mainly on that polymer. A chemical analysis of the polymer is used to identify some characteristics and identify knowledge gaps, without going deep into the specific chemistry.

2 Theory

This chapter will establish the theoretical framework for this thesis and set some definitions used for those terms.

2.1 Defining Circular Economy

Although the term ”circular economy” has become more and more popular, the CE concept has been interpreted and implemented in a variety of ways, according to Kirchherr et al. (2017). Their systematic analysis of 114 definitions featured 95 different CE definitions, further backing their claim. By revisiting this analysis, Kirchherr et al. (2023) found that ”the 221 definitions in this study reflect an understanding of CE both more consolidated and more differentiated”. Furthermore, they state that 70-80 percent of the articles recognise ”recycling” and ”reuse” as two of the fundamental principles of CE.

Using the EU’s strategy for plastics, the European Commission identified some key actions for authorities and industry (European Commission 2018). One of the main actions were ”Improving the economics and quality of plastics recycling”, which includes working together to:

- Improve design and support innovation to make plastics and plastic products easier to recycle.
- Expand and improve the separate collection of plastic waste, to ensure quality inputs to the recycling industry.
- Create viable markets for recycled and renewable plastics.

Overall, implementing these CE principles can contribute to the sustainability of the aquaculture industry while providing economic and environmental benefits.

2.2 Research-industry collaboration

Research-industry collaboration is considered an essential input to innovation (OECD 2015), and vital in ”stimulating open innovation that leads to new products, processes and services that creates value [for broader societal impact]” (Fernandes et al. 2023). Structured and mutually beneficial partnerships between research and industry can lead to problem-driven, co-creative and directly applicable discoveries Kotiranta et al. (2020). Furthermore, collaboration significantly improve the research and teaching activity for the universities.

To address the environmental challenges we face today, a trans-disciplinary approach including natural sciences, social sciences, engineering and management is essential. The complexity of the CE model raises several practical challenges that require experts from diverse disciplines to resolve (Sauvé et al. 2016).

2.3 Plastic polymers

Many kinds of PE are known, with most having the chemical formula (C2H4)n (with n referring to the degree of polymerisation) (Basmage & Hashmi 2020, Kurtz 2016). The different types of PE is classified by their density and branching, which can be altered during processing to affect variables such as chain length, density and crystallinity (Dhakal & Ismail 2021). These variables, along with branching, have a significant effect on the mechanical properties (Basmage & Hashmi 2020).

As stated in subsection 1.2, the producer in this study uses HDPE for their aquaculture-products. HDPE is one of the most important sub-types of PE, which also includes LDPE and linear low-density PE (LLDPE). Compared to LDPE and LLDPE, HPDE contains a more linear morphology, a higher crystallinity, and minimal branching. It is also lightweight and have good tensile strength (Dhakal & Ismail 2021). The degree of branching in the different types of PE is represented in Figure 1.

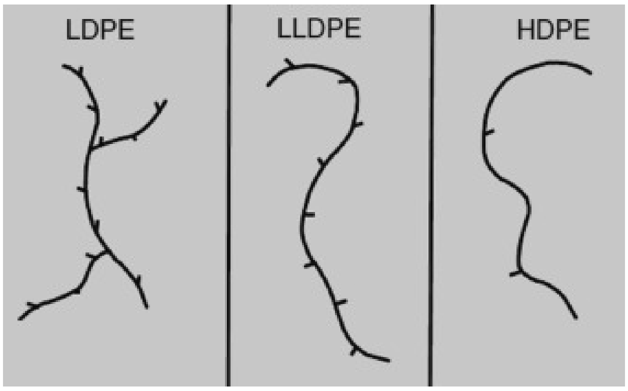


Figure 1: *Types of PE according to structure. From Kupolati et al. (2017).*

2.4 Plastic Associated Chemicals

Additives are often added to the plastic polymers, in order to change the properties. Some common additives are thermal stabilisers, UV stabilisers, anti-static agents, slip agents, flame retardants and more (Hahladakis et al. 2018). According to Hahladakis et al. (2018), several of these additives could lead to a release of hazardous substances during the recycling process, especially during moulding and extrusion which are often operated at 200-300°C.

In addition to additives, which are intentional, the term ”plastic associated chemicals” (PAC's) also includes any chemicals attained in other ways. This could be by-products from the production process, chemicals absorbed/adsorbed during usage phase, created due to UV radiation, heating during production or recycling, or any residues.

There is a big knowledge gap regarding PAC's, as not all information is passed from the plastic producer to the next level in the value chain, which was further expressed in the company visits (subsection 4.1). It is also difficult to analyse additives incorporated into plastic materials due to small concentrations and the complexity and difficulties in extracting the additive from the material.

2.5 Pyrolysis–Gas Chromatography–Mass Spectrometry

After acquiring the samples, one of the most relevant methods for chemical analysis are variations of the Pyrolysis-Gas Chromatography Mass Spectrometry (Py-GC/MS) method. The specific application and parameters used is explained in subsubsection 3.3.2.

PY-GC/MS is a technique which uses heat to break down the large, high-molecular weight molecules in a sample to create smaller low-molecular weight moieties. These moieties can then be separated by gas chromatography and their composition determined by mass spectrometry. This gives information on the structural composition of the original high-molecular molecules in the sample so the sample composition can be identified (Crawford & Quinn 2017).

This method requires some pre-treatment but can then analysed directly. It can be utilised to identify both microplastics and plastic additives present in the samples simultaneously. However, the analysis of large quantities and the range of particle sizes which can be handled is limited. Since the particles requires manually placement in a pyrolysis tube, there is also a limit on the minimum and maximum size of particles to be analysed (Crawford & Quinn 2017, Zobkov & Esiukova 2018). The Py-GC/MS method only uses a very small sample size, where sizes from 5-200 μg is commonly used (Chandrasekaran & Sharma 2019, Schinazi et al. 2022).

According to Primpke et al. (2020), thermo-analytical methods such as Py-GC/MS are so far the only possibility to reliably determine polymer-type masses. Nevertheless, Primpke et al. (2020) also recommends caution and experience when interpreting the data due to its complexity.

3 Methodology

3.1 Literature review

For the theoretical framework for this paper, a narrow literature review was used to collect information and find knowledge gaps related to aquaculture gears, PAC's and the role of plastics in CE, as well as relevant methods for analysing polymers. Along with the literature review, some articles were provided by the supervisor, co-supervisor or has been curriculum in previous courses, Relevant reports from big organisations (e.g. like EU) or industry stakeholders have also been used.

As described by Deshpande (2020), a ”narrow review is aimed at filtering limited literature to address specific research questions with a focus on relevance rather than comprehensiveness.” The specific research questions have been developed from the gaps and barriers pointed out by the case companies.

3.2 Company visits and interviews

Visits were done with a local plastic product producer and plastic waste recycler in Norway, both related to the aquaculture industry. During the company visits, a semi-structured interview was done, following some guiding questions which can be seen in Appendix A. The semi-structured interview is good for gathering systemic information about some central topics, while allowing the freedom to explore unexpected topics that emerge (Wilson 2014). Further information about the companies and findings from the visits can be seen in subsection 4.1.

During the visits, samples of plastics were also acquired. The recycler provided samples of different ropes, fishnets, feed pipes and farms, and processed granulates/pellets. The pellets and feed pipes can bee seen in Figure 2 and white feed pipes in Figure 3.

Figure 2: *Two feed pipe samples acquired from the recycler. The top one is washed and coarsely ground, while the bottom have been melted into pellets.*

Figure 3: *White feed pipe sample acquired from the recycler. The carbon black stripe is to prevent static electricity, and makes the polymer a uniform black after melting.*

From the producer, pellets for both the virgin and non-virgin polymers they use were attained.

3.3 Sample preparation and analysis

After acquiring the samples, the following methods were used for preparing and analysing samples. The analysed samples were virgin and recycled polymer samples attained from the producer; black feed pipe and white feed pipe from the recycler; and pellets made from feed pipes, also from the recycler.

3.3.1 Cryogenic grinding

As mentioned in subsection 2.5, the methods used requires small particle sizes. Therefore, cryogenic grinding, also referred to as ”Cryomilling”, was used to reduce the initial sample to smaller particle sizes.

Before milling, the sample was cut, cleaned with methanol, weighed and put

in the milling container, all while using gloves and clean surfaces to prevent sample contamination. The sample was then chilled for 5 minutes using liquid nitrogen, then milled using a Frontier Lab Cryogenic Mill (IQ MILL-2070). The milling was done at 3000rpm, with 20s rotation time and 20s pause time for 3 cycles.
The chilling and milling process was all done 3 times to ensure small enough particle size. Approximately 0,5g of every sample was milled.

3.3.2 Pyrolysis–Gas Chromatography/Mass Spectrometry

The Py-GC/MS method was done using a Fronier Auto-Shot Sampler AS-1020E for the pyrolysis along with Agilent 8860 GC System for the gas-chromatography and Agilent 5977B GC/MSD as the mass spectrometry unit.

As mentioned in subsection 2.5, the method only needs a small amount of sample. Therefore, the samples were between 130-150 μg, measured using a weight with uncertainty of ± 5 μg. Between every sample, a blank sample was run to clear the machine of any residues. At the end of every session, a control sample was added. The control sample was used to remove background noise in the results, and to recognise any possible sample contamination.

All the settings used for the Single-shot Py-GC/MS method can be seen in Table 2.

Table 2: *Settings for single-shot Py-GC/MS analysis*

Unit	Parameter	Setting
Pyrolysis	Chamber temperature	550°C
	Pyrolysis time	12s
GC	Carrier gas	Helium
	Column flow rate	1mL/min
	Split ratio	1/50
	Oven temperature	50-300°C at 10°C/min 15 min hold at 300°C
MS	GC/MS interface temperature	300°C
	Scan range	25-500 m/z

To look for additives, a slightly different method is needed. In the Thermal Desorption - py-GC/MS (TD-Py-GC/MS) method, the volatile compounds are analysed by thermal desorption before the pyrolysis. This separates the components from the polymer, simplifying identifications Frontier Lab (n.d.). All the settings used for the TD-Py-GC/MS method can be seen in Table 3.

Table 3: *Settings for TD-Py-GC/MS analysis*

Unit	Parameter	Setting
Pyrolysis	Initial temperature, hold time	100°C, 12s
	Temperature program	100-400°C at 20°C/min 48s hold at 400°C 400-550°C at 150°C/min
GC	Carrier gas	Helium
	Column flow rate	1mL/min
	Split ratio	1/50
	Oven temperature	50-300°C at 10°C/min 15 min hold at 300°C
MS	GC/MS interface temperature	300°C
	Scan range	25-1000 m/z

After getting py-GC/MS-data, the chromatograms were processed in Agilent's "MassHunter Qualitative Analysis 10.0" program, where they were layered and scaled to the highest peak. The peak data was collected and integrated in order to compare the peak area ratio for the different polymers, as the area corresponds to concentration. No quantitative analysis was done, just a semi-quantitative analysis when looking at the concentration.

When looking at the unknown peaks, "FSearch MPs 2.0" from FrontierLab was used to compare the mass-spectrometry to a library of substances. All in all, very good assistance was provided (by co-supervisor) in interpreting the mass spectrometries and chromatograms.

4 Results

4.1 Visit with producer

This section explains some of the main findings from the visit with the plastic producer.

The main products from the producer for the aquaculture industry are brackets and walkways (see Figure 4,Figure 5), which account for 60% and 40% of plastic volume, respectively. Both products are made from HDPE. However, the brackets are made from pristine material, while the walkways are made from 100% non-virgin material recycled from pipes.

Figure 4: *Brackets produced for an aquaculture fish farm.*

Figure 5: *Walkways produced for an aquculture fish farm.*

Production with recycled polymers started in 2021, with the idea for the project dating back to 2014. This project have resulted in a 40% reduction of virgin material, amounting to 700 tonnes annually – and 1,6 tonnes CO2 equivalents saved for every tonne plastic. They also reuse waste from other production lines with the same polymers in order to reduce waste from those other products. Figure 6 illustrates the idea behind the project, and how they work towards ”closing the loop”.

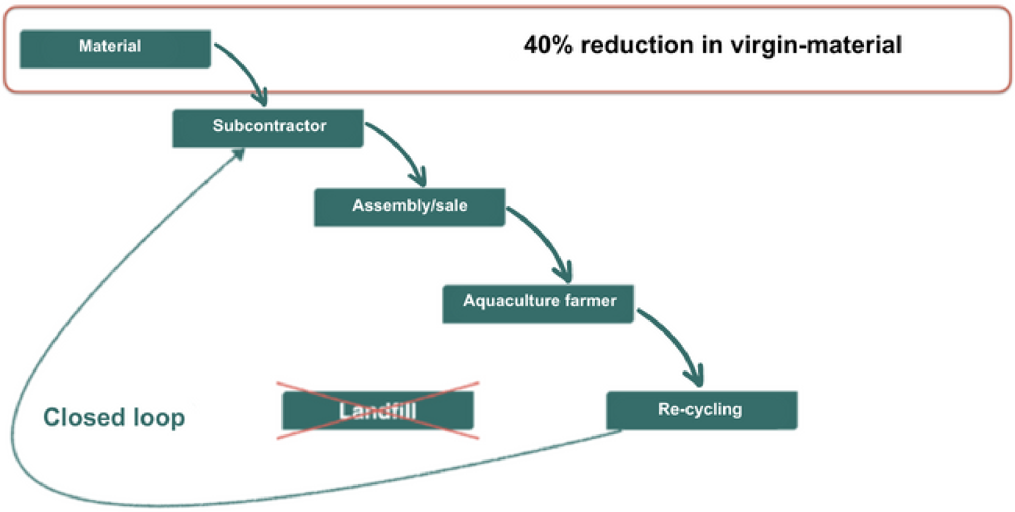
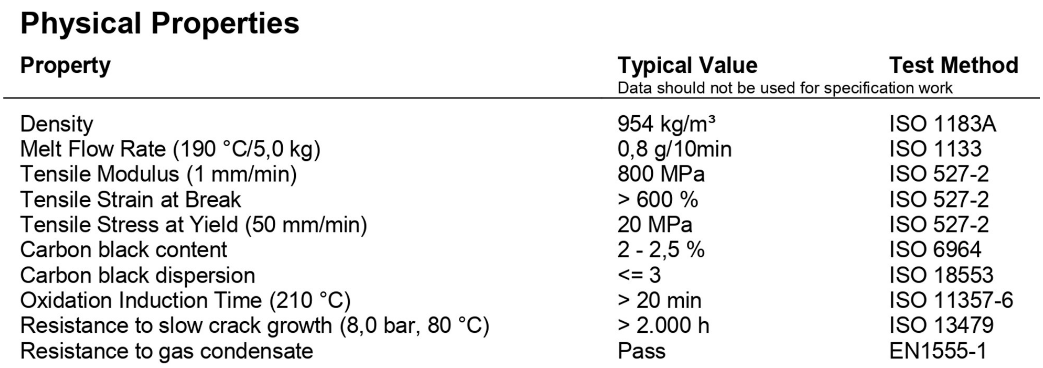


Figure 6: *Illustration of a closed loop material chain from the producer*

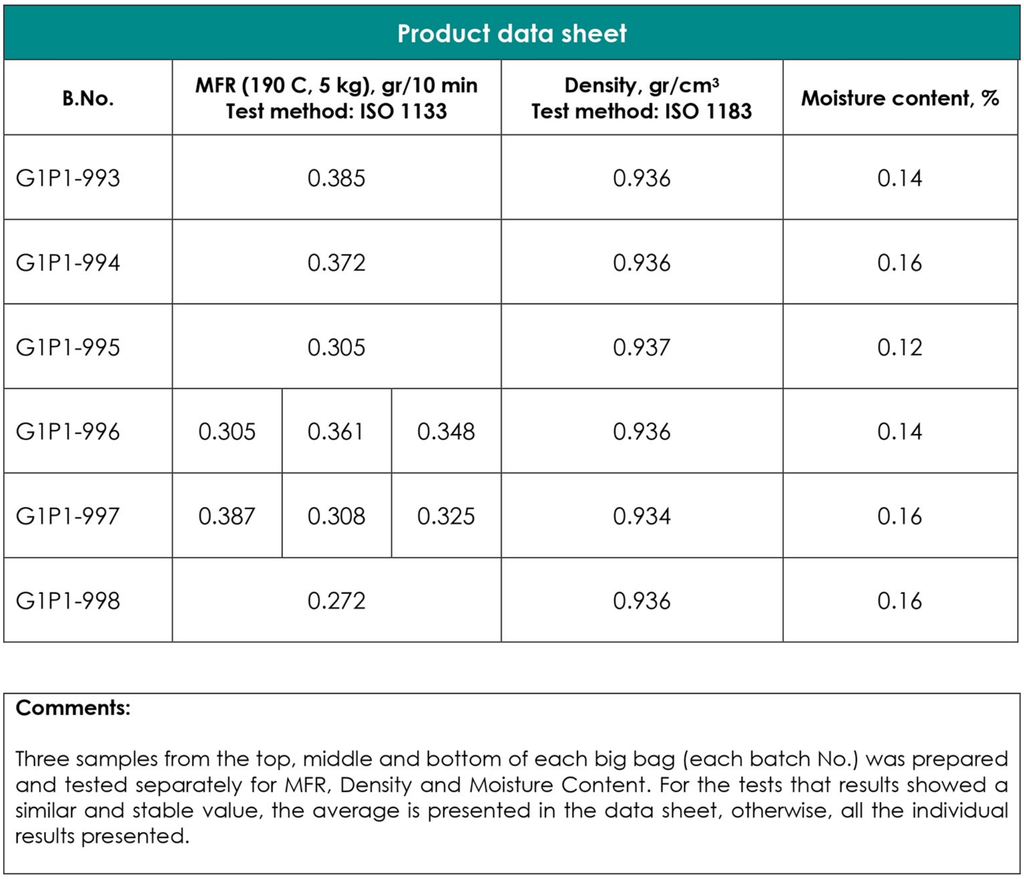
Interestingly, the tensile strength is higher for the recycled material compared to virgin, due to usage of HDPE100 instead of HDPE80 (the number referring to length of the polymer). However, they observe reduced MFR for the recycled polymer compared to the virgin polymer (this can be seen in Figure 7 and Figure 8; MFR of 0,8 g/10min for virgin polymer vs. 0,272-0387[low-high] g/10min for the recycled polymer). This is one of the biggest challenges they face, as it slows down the production speed.



Physical Properties

Property	Typical Value Data should not be used for specification work	Test Method
Density	954 kg/m³	ISO 1183A
Melt Flow Rate (190 °C/5,0 kg)	0,8 g/10min	ISO 1133
Tensile Modulus (1 mm/min)	800 MPa	ISO 527-2
Tensile Strain at Break	> 600 %	ISO 527-2
Tensile Stress at Yield (50 mm/min)	20 MPa	ISO 527-2
Carbon black content	2 - 2,5 %	ISO 6964
Carbon black dispersion	<= 3	ISO 18553
Oxidation Induction Time (210 °C)	> 20 min	ISO 11357-6
Resistance to slow crack growth (8,0 bar, 80 °C)	> 2.000 h	ISO 13479
Resistance to gas condensate	Pass	EN1555-1

Figure 7: *Extract from product data sheet for virgin HDPE 80 polymer.*



Product data sheet

B.No.	MFR (190 C, 5 kg), gr/10 min Test method: ISO 1133			Density, gr/cm³ Test method: ISO 1183	Moisture content, %
G1P1-993	0.385			0.936	0.14
G1P1-994	0.372			0.936	0.16
G1P1-995	0.305			0.937	0.12
G1P1-996	0.305	0.361	0.348	0.936	0.14
G1P1-997	0.387	0.308	0.325	0.934	0.16
G1P1-998	0.272			0.936	0.16

Comments:

Three samples from the top, middle and bottom of each big bag (each batch No.) was prepared and tested separately for MFR, Density and Moisture Content. For the tests that results showed a similar and stable value, the average is presented in the data sheet, otherwise, all the individual results presented.

Figure 8: *Product data sheet for recycled HDPE 100 polymer.*

According to the producer, another one of the biggest limiting factor in closing the loop and using recycled materials for brackets are industry standards, which limits/complicates the use of recyclates. Demand for material quality is regulated by a technical standard, NS 9415 (2009). Therefore, today, virgin polymers are not used for any load-bearing construction in the farms.

The producer, among others (the main contractor, recycler, and other companies), are trying to affect the standards so they can be updated to new knowledge. They are also investigating how much recycled materials can be used while still maintaining physical properties for the brackets, as strength cannot be compromised.

The producer referred to an ongoing research project on simulated usage cycles - showing maximum melting cycles for polymers is 7, giving 3,5 usage cycles (2 melting cycles per usage cycle). According to the study, melting cycles affects the polymer properties a lot more than the usage phase, making the material more brittle with cycles.

They would also like to see a more unified system with material certificate being passed (and used) from producer to user to recycler for less convoluted and better recycling/circularity process.

4.2 Visit with recycler

The recycler started as a general waste management company, and later evolved into waste management from aquaculture and fisheries. Today they have manage 25 thousand tonnes of waste annually, of which approximately 10 thousand tonnes are plastics. Of the plastic waste, around 4 thousand tonnes are different types of ropes.

Some of the plastic is recycled, where 20 % of the recycled plastics are used for new products in Norway, while 80 % of the recycled granulates are sold internationally, mostly to Sweden and Czech Republic.

Most of the costumers use ”downcycled” plastic polymers. It is easier to recycle high-quality plastic polymers for products with lower quality standards/demands than to retain the qualities and physical properties to make similar products (e.g., new ropes from the same polymers).

The whole process of waste management is quite complex and intricated, with many factors making the process more difficult. Sorting the waste is difficult and tedious, especially if it not done early in the process. Therefore, recycler prefers to collect the waste themselves whenever possible, allowing for sorting at an early stage. Mixing of gear, ropes and polymers makes for a time consuming sorting stage. After sorting, the polymers are washed, roughly ground (making it easier to transport), before making plastic pellets. The recycler does physical tests for the recycled pellets, but no chemical testing is done.

Another challenge for the recycler is lack of knowledge on the polymers. There is a big variation on type of PE in feed pipes, and gaps in knowledge. They further stress the need for a uniform system or database, where every link in the value chain will receive info on the products/polymers.

Also worth noting is the ”consumer power” - here meaning the user (consumer) of plastic products, i.e. the fish farmers. As a waste recycler, one must adapt to new types of products and wastes. As a result, much of the decision-making and influence lies with the aquaculture farmers, not the recycler.

4.3 Material composition

This section describes the results from the lab-analysis of the samples.

The peaks we see in Figure 9 and Figure 11 represent carbon chains of different lengths. After the polymer is broken down, the pyrolyzates will exit at different retention times, corresponding to the length of the compound. These carbon chains may be referred to as ”C18” or ”C35”, with the number referring to the number of carbon atoms in the chain. The peak areas can be used to look at the ratio and distribution of compound lengths (Figure 10).

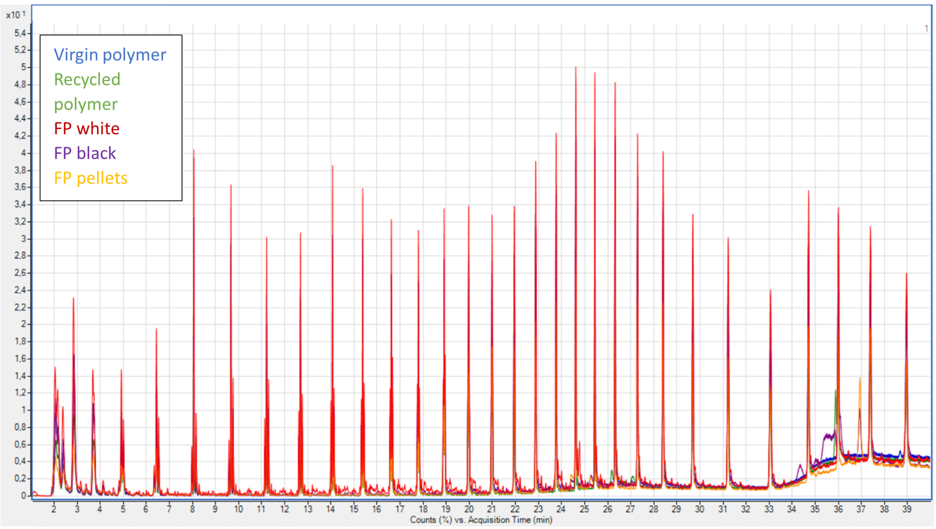


Figure 9: *Chromatograms from the single-shot method (layered and scaled to the highest peak).*

As we can see from Figure 10, the virgin polymer contains significantly less of the longer-chained compounds in the polymer. The virgin polymer was said to be HDPE80, while the recycled polymer is HDPE100. The number is again referring to the length of the polymer, with HDPE100 having longer polymer chains than HDPE80.

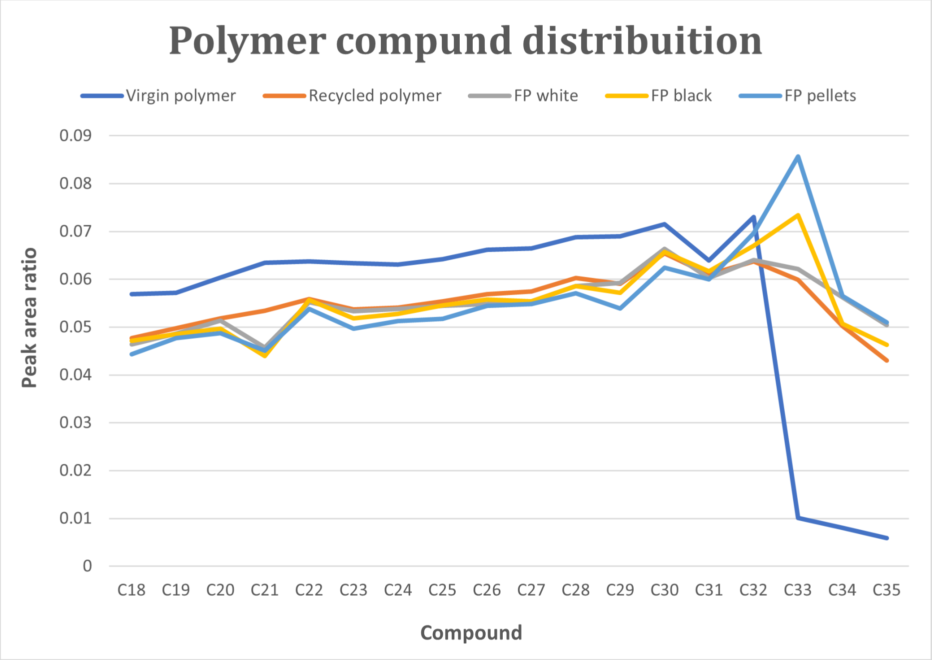


Figure 10: *Ratio between compound peak areas and total area of compounds C18-C35 in the polymers.*

Even though the recycled polymer has longer carbon chains than the virgin polymer, the density is lower (see Figure 7 and Figure 8 for density values of both polymers). This might be caused by branching during the melting and usage cycles. This theory is supported by Pinheiro et al. (2004), stating thermo-mechanical degradation have shown to produce chain branching in HDPE. Abbas-Abadi et al. (2022) also observed more branching and lighter products in EOL-polyethylene. However, Abbas-Abadi et al. (2022) also included mechanical degradation and UV degradation as reasons for this.

4.3.1 Plastic associated chemicals

Neither the producer nor the recycler uses any additives themselves. The provider of the virgin polymer was contacted regarding additives but with no response. The product sheet for the virgin polymer includes physical properties, but no specific information on additives used aside from ”a combination of pigments and stabilisers to ensure excellent long-term stability and UV resistance.”

The producer stated the biggest challenge in using additives is resource demand. It takes a lot of resources to find what type and quantity to use.

They stated that a master batch for additives would be one of the most beneficial research inputs for the future. This could give the ability to potentially restore the qualities of the polymer lost during the recycling process, and the ability to control physical properties. Specifically additives like flow enhancers that do not affect other critical properties, as reduced MFR is one of the main challenges for recycled polymers. This would help give the polymers longer life (in terms of ability to withstand more recycling cycles and avoid downcycling).

As mentioned in subsubsection 3.3.2, a slightly different method was used to look for additives. Along with the carbon chain peaks seen in Figure 9, we can also see some small peaks before the polymer in Figure 11, which corresponds to different PAC's.

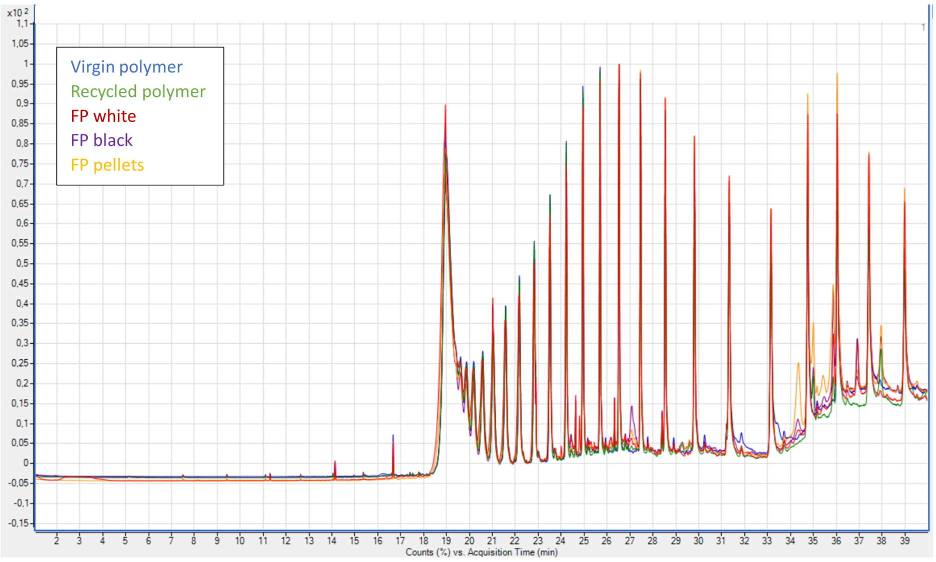


Figure 11: *Chromatograms (layered and scaled to the highest peak) from the TD-Py-GC/MS method.*

The two peaks at retention time 14,13 min and 16,67 min will be referenced to as additive peak 1 and 2, respectively. They can be seen closer in Figure 12 and Figure 13, which are zoomed in to the additive peaks.

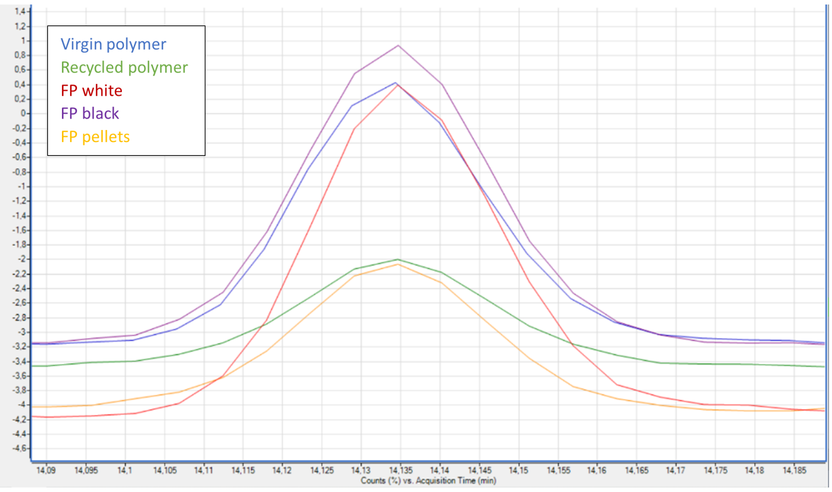


Figure 12: *Chromatograms from TD-Py-GC/MS, scaled to the largest peak and zoomed in to additive peak 1.*

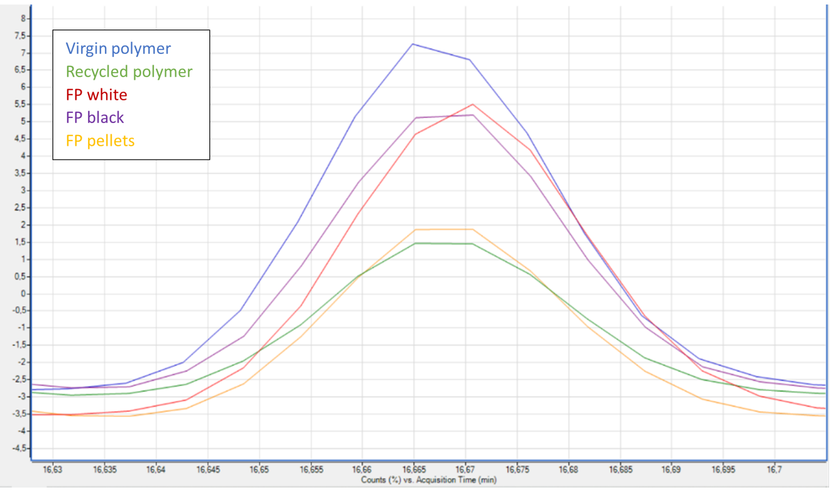


Figure 13: *Chromatograms from TD-Py-GC/MS, scaled to the largest peak and zoomed in to additive peak 2.*

Figure 12 and Figure 13 shows how the virgin polymer contains significantly more of the additives compared to the recycled polymers. The first-generation feed pipes also contains more additives than the recycled polymer and the feed pipe pellets.

This is better illustrated when the peak areas are compared in Figure 14. For the first peak, the two types of feeding pipes seem to have the same values as the virgin polymer, while the recycled polymer and pellets have much lower.

The difference in additives is even higher in the second peak, where it seems there is a loss of additive from the virgin material to the first-generation products and even more to the polymers that have gone through two melting cycles.

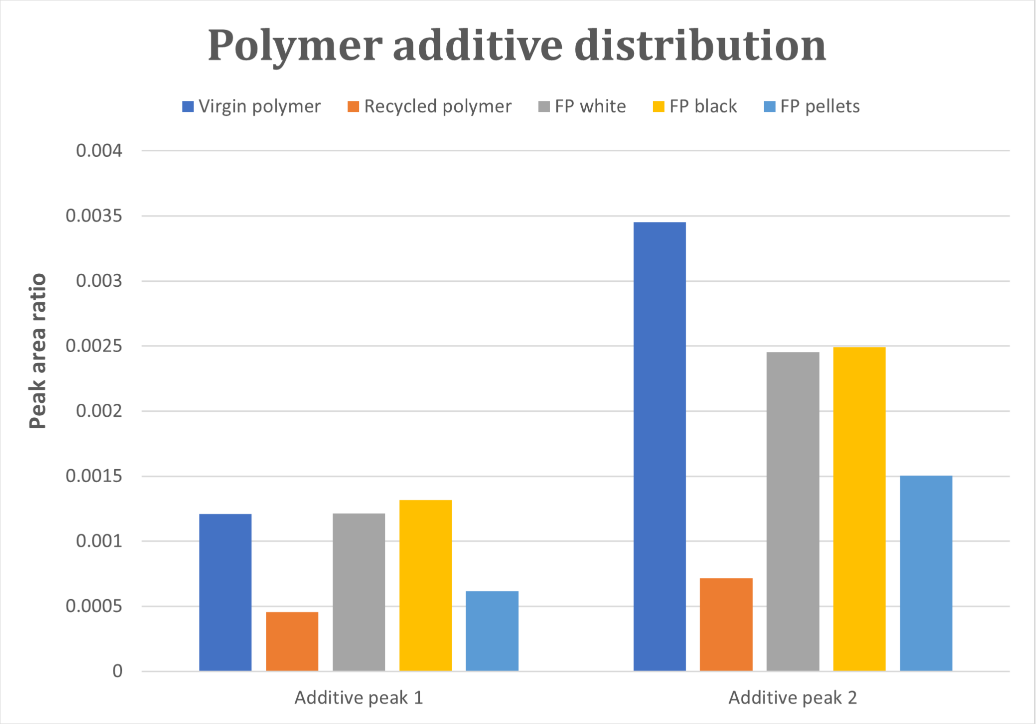


Figure 14: *Ratio between additive peak areas and total area of compounds C18-C35 in the polymers.*

The mass spectrometry for both peaks can bee seen in Figure 15 and Figure 16. With help from the co-supervisor, the spectrometries were qualitatively analysed. The pyrolysis products for additive peak one and two were n-pentadecane (C15 alkane) and n-hexadecane (C15 alkane), respectively.

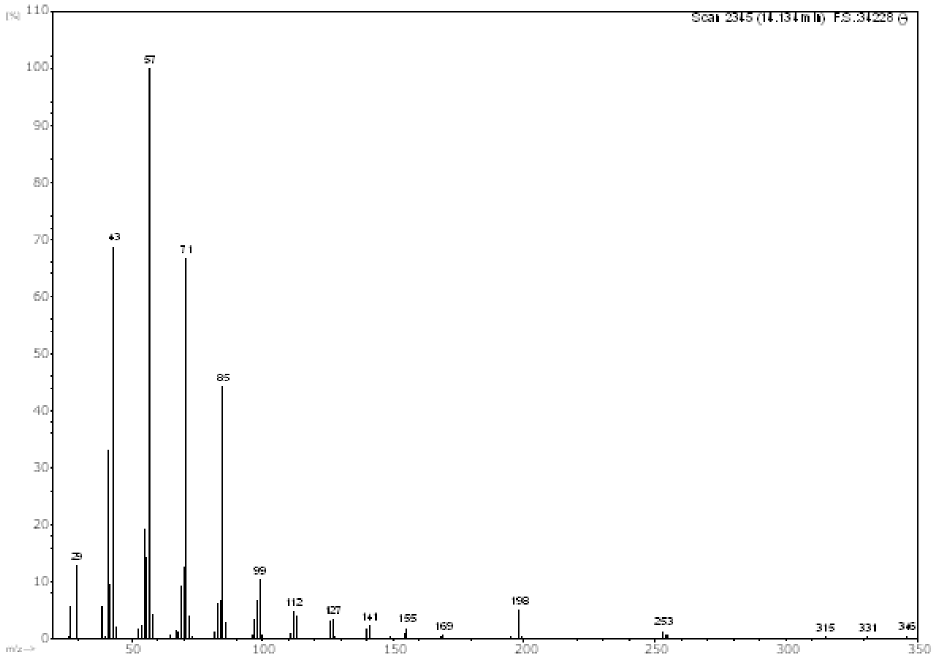


__Figure 15:__ Mass spectrometry for additive peak 1, with background subtracted.

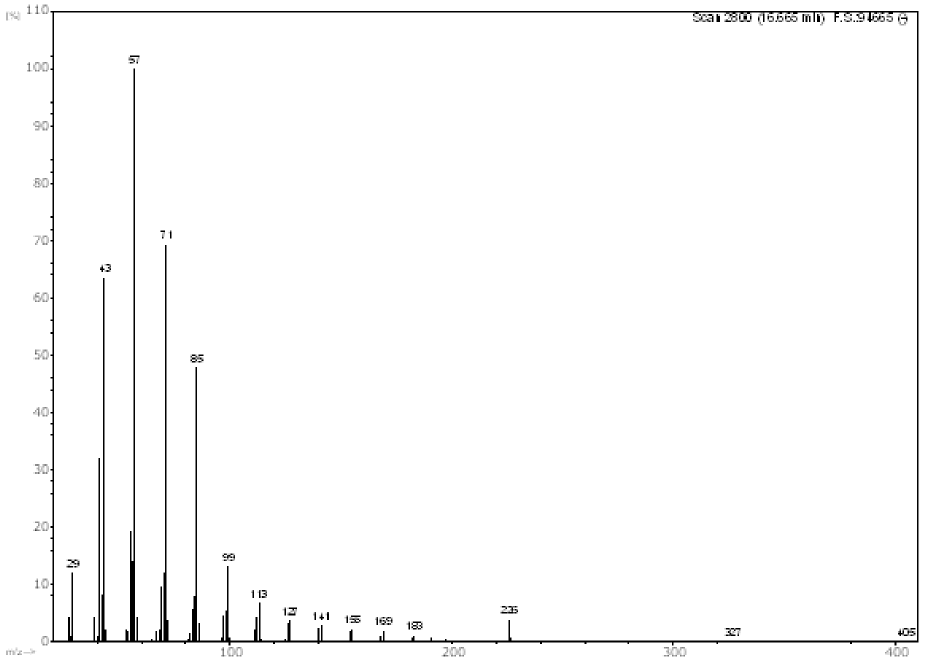


__Figure 16:__ Mass spectrometry for additive peak 2, with background subtracted.

Although methods to simultaneously determine various additives in polymers (on regulatory levels) are still underdeveloped Yanagisawa et al. (2019), the reference material from the FSearch library identified these as some of the possible substances the PAC's could be:

- Fatty acids, monton wax
- Glycerides, montan-wax
- Metal stearate (Al, Ca, Zn or Mg)
- Partially esterified montan wax

Although certain identification of the PAC's requires further investigation and a more precise py-GC/MS method, the pyrolysis product is a fragment from a fatty acid, and likely comes from a wax or stearate. These can be used as slip agents, which are one of the most common additives (Bishop 2015). The recycler claimed the black lines in the white feeding pipes (Figure 3) to be for anti-static purposes. This could be an indicator of some sort of anti-static agents in the product, though this needs to be confirmed.

loss of the unknown additive from virgin polymer to feed pipes to recycled polymers.

5 Discussion

5.1 Current state of CE in Norwegian aquaculture

Even though recycling has increased in the last years, only 33% of total waste is currently recycled (Systemiq et al. 2023*a*). Up until 2020, virgin plastics accounted for 100% of plastics. However, research-industry collaborations are starting to lead to new solutions and production patterns, with good progress being made towards fish farms made from 100% recycled plastics (Olafsen n.d.). The producer in this study have started producing walkways from recycled polymers, and are exploring opportunities to also use recycled plastics in the brackets. However, the current recycled plastics are downcycled from higher quality polymers, which does not entirely close the loop. Nevertheless, the project is a huge step in the right direction, and important in building momentum for change.

Demand for virgin plastics can be heavily reduced in the future, while still meeting the increasing demands for production. With systemic changes, the aquaculture have good potential for high circularity - with a shift to 81% circularity by 2040 within reach (Systemiq et al. 2023*a*). On the way towards this circularity, several challenges emerge.

5.2 Challenges towards reaching higher circularity

5.2.1 Physical distances

One of the challenges towards higher circularity is the role of physical distances in value chain, particularly the waste management and recycling process. Havas et al. (2022) have coined this concept ”Small Circles” (SC), which is defined as “Reshaping the circularity strategies through containment of the geographical boundaries of end-of-life products to avoid financial, material and energy losses, and to ensure transparency and resilience in implementing strategies for the circular economy.”

Havas et al. (2022) further describe SC as an approach advocating the need for waste management within a smaller area of its origin. The aim is to reduce environmental burdens related to shipping and export of waste, such as emissions from transport and waste-leakage. Moreover, this would ensure that waste-producing regions take responsibility for their waste generation and management, and could improve transparency regarding the fate of the waste. To achieve this, physical distance should be included as an indicator in targets for plastic recycling.

The recycler in this study currently exports 80% of the recycled polymers internationally, to countries like Czechia and Sweden amongst others, while 20% remains in Norway. Other stakeholders have determined transport-related emissions as a barrier for recycling, and recommend using local waste managers instead (NorseAqua n.d.). The concept of SC would also benefit the problem of unmanaged and unregulated export of waste to developing countries, which could be a risk for the SDGs (Garcia-Saravia Ortiz-de-Montellano et al. 2023).

Even though Havas et al. (2022) states ”the implementation of the SC approach may have high initial investment costs due to the restructuring of value chains and establishment of improved coordination of stakeholder actions throughout the product life cycle”, Systemiq et al. (2023*b*) claims that a system change scenario is the most economical for durable plastics as it drives resource and capital efficiency.

5.2.2 Material challenges

Changes in physical properties of the material lead to further challenges. The main property which poses challenges in the polymer is the loss of MFR, which results in higher production costs due to longer cycle times in production. This negates the financial benefits of a (slightly) cheaper recycled polymer. This might be caused by loss of slip agent additives. Solving the MFR problem would increase efficiency and economic profit from recycled polymers.

After several melt cycles, they observe a more brittle material. This limits the amount of melt cycles, as the quality of the product is reduced every time. A lower density is observed for the recycled plastics, and literature and chemical analysis indicates branching and/or scission could be the reason for this. However, the use of different length polymers (HDPE80 and HDPE100) makes it harder to draw a definitive, clear-cut conclusion.

Despite this, the physical properties are still within the standard for several cycles. By re-recycling second- or third-generation plastic products, this could pose a bigger problem down the line unless a solution to restoring quality have been found, by further complicating the sorting process, which is already a complex and convoluted process. Lack of knowledge on the plastics reduces efficiency and quality of the recycling.

A material tracking system which gives information (data sheest with physical properties, tracking of usage cycles, polymer history, etc.) about products and polymers would bring clarity to the process and help guarantee higher polymer standard. With a good system, downcycling could be further put off or avoided by allowing for more cycles.

A guarantee of higher standard would also insure the polymer being within the technical standards. The producer is working to affect the policy-makers to possibly update the standards, which is currently limiting for the use of virgin-polymers. At the same time they are working towards getting the recycled polymers approved within the standards. Olafsen (n.d.) states their project is mainly working towards proving the quality of the recycled plastics, rather than challenging the standard, but still consider it a limiting factor.

5.3 Moving forward towards closing the loop

The main views and challenges raised by the producer and recycler is also identified in literature as key focus points when moving forward. Figure 17 shows the key recommendations towards higher circularity presented in Systemiq et al. (2023*a*).

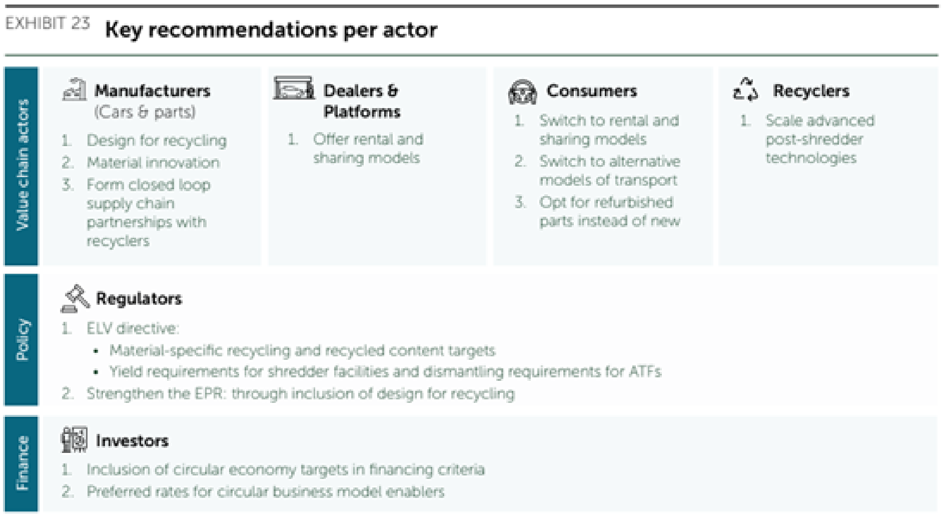


EXHIBIT 23 **Key recommendations per actor**

Value chain actors

Manufacturers (Cars & parts)
1. Design for recycling
2. Material innovation
3. Form closed loop supply chain partnerships with recyclers

Dealers & Platforms
1. Offer rental and sharing models

Consumers
1. Switch to rental and sharing models
2. Switch to alternative models of transport
3. Opt for refurbished parts instead of new

Recyclers
1. Scale advanced post-shredder technologies

Policy

Regulators
1. ELV directive:
    - Material-specific recycling and recycled content targets
    - Yield requirements for shredder facilities and dismantling requirements for ATFs
2. Strengthen the EPR: through inclusion of design for recycling

Finance

Investors
1. Inclusion of circular economy targets in financing criteria
2. Preferred rates for circular business model enablers

Figure 17: *Key recommendations to achieve circularity for fisheries and aquaculture sectors.*

In addition to these points, they also recommend product/material tracking to guarantee documentation on risk analysis for recycled products. This tracking is one of the requested points from the case companies in this study.

Presently, there is a high focus on physical properties of polymers. At the moment, physical testing is commonly done for the products, but seldom chemical testing. Including chemical analysis can supplement our understanding of the polymers and how they change during recycling process, which in turn can solve some of the challenges related to physical properties. While physical properties are important to get the product approved within the current standards, a better chemical understanding can also give a better foundation for arguments towards updating the standard.

Interdisciplinary research and research-industry collaborations is needed to thoroughly solve the material challenges and fully integrate material sciences into the CE model. Continuation of the current and participation of future research-industry collaborations is important to drive innovation towards CE.

5.4 The role of plastic associated chemicals

Plastic associated chemicals can currently be considered as an 'X-factor' in the recycling process. The loss of an unknown PAC's during the recycling process (subsubsection 4.3.1) could be part of the reason behind some of the physical changes observed. This is good ground for further work, as the possibility to re-introduce additives would increase our ability to control the changes. Increasing MFR without affecting the plastic quality would increase efficiency and economic profit from recycled polymers, giving further incentive towards adopting a circular business model.

Ideally, in this project, more time should have been available to test and develop the Py-GC/MS-method, which could have provided better results for identifying the PAC's. Although this identification is possible, simultaneously determining various additives in the polymers is still fairly new and recently underdeveloped method. Remarkable progress towards practical use have been made in the last few years (Yanagisawa et al. 2019). Still, Primpke et al. (2020) recommends caution and experience when interpreting the data due to its complexity.

Although it is outside the scope of this thesis, the release of hazardous substances during the recycling process is another reason to look closer at PAC's in the plastic. Caution must be used when recycling a polymer containing a potentially toxic additive into new products with more sensitive use areas Hahladakis et al. (2018). Another example of this is PVC. Even though PVC is tough and weathers well, it is rarely recycled and should not be burnt as it releases toxins (Huntington 2019).

5.5 Limitations

For a more holistic view, this would ideally contain more case companies, including aquaculture farmers and virgin polymer manufacturers. The virgin polymer manufacturer was contacted to attempt to gain information on additives in the polymer, with no luck. More waste management companies might have brought up more varied views to examine. Additionally, interviews with material scientists could improve the expertise behind the material analysis.

Fourier-transform infrared spectroscopy (FTIR) -analysis was done to look for oxidation, but due to time constraints the interpretation was dropped. The method and results are briefly explained in Appendix B.

6 Conclusion

Although the Norwegian aquaculture sector is quite linear, there is very good potential for high circularity with adoption of systemic changes. Current practices for realising higher circularity include closed loop partnerships between manufacturer, sub-contractors and recyclers. The case companies are active in research-industry collaborations, and working to develop polymers and products that are within the standards, even for bearing structures of the fish farms. At the same time, they are also pushing to affect the standards towards allowing more recycled polymers.

For material properties, there is a high focus on physical properties and the industry would benefit from including chemical analyses to the material science. Waste management is a complex process, and especially the sorting process is demanding for the recycler. Product/material tracking systems for polymer documentation would be beneficial for the recycler.

As discussed in subsection 5.4, PAC's can presently considered an 'X-factor'. There are currently big knowledge gaps regarding PAC's and additives, and lack of information from plastic polymer supplier. A loss of PAC's was seen in the polymers after each melt cycle, but further work is needed to properly identify these additives, their physical effects and impacts. Figuring out how to re-introduce or replace them in the polymers would be extremely beneficial, and result in an increase in efficiency which in turn leads to higher economic incentive towards using more recycled polymers.

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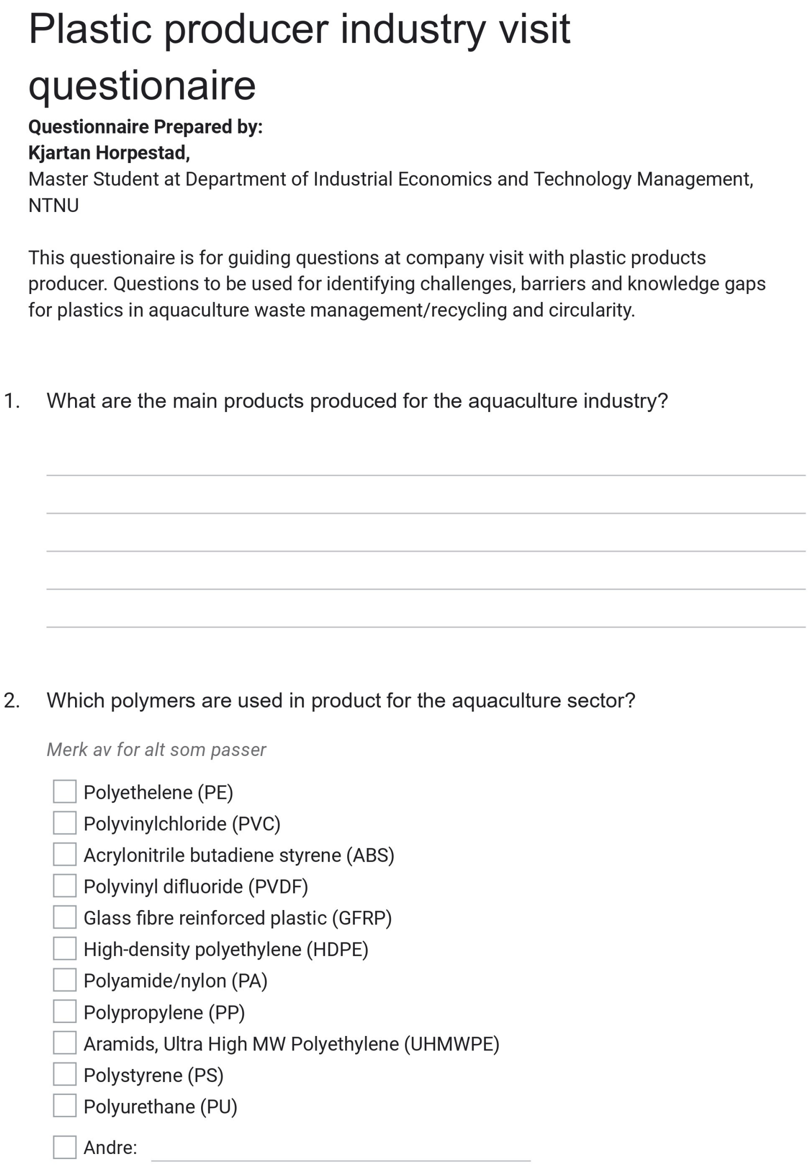
A Company visit questionnaire



Plastic producer industry visit questionaire

Questionnaire Prepared by:
Kjartan Horpestad,
Master Student at Department of Industrial Economics and Technology Management, NTNU

This questionaire is for guiding questions at company visit with plastic products producer. Questions to be used for identifying challenges, barriers and knowledge gaps for plastics in aquaculture waste management/recycling and circularity.

1. What are the main products produced for the aquaculture industry?

2. Which polymers are used in product for the aquaculture sector?

Merk av for alt som passer

☐ Polyethelene (PE)
☐ Polyvinylchloride (PVC)
☐ Acrylonitrile butadiene styrene (ABS)
☐ Polyvinyl difluoride (PVDF)
☐ Glass fibre reinforced plastic (GFRP)
☐ High-density polyethylene (HDPE)
☐ Polyamide/nylon (PA)
☐ Polypropylene (PP)
☐ Aramids, Ultra High MW Polyethylene (UHMWPE)
☐ Polystyrene (PS)
☐ Polyurethane (PU)
☐ Andre:

Figure 18: *Questionnaire with guiding questions for company visit.*

3. What is the source of the different virgin polymers used for Aquaculture equipment?

4. What percentage of material used is recycled/non-virgin plastic?

5. Are all the recycled/non-virgin polymers used sourced nationally?

6. Are there any barriers in using recycled materials? What are the current solutions?

7. What plastic associated chemicals (PAC's) are in the materials used? (recycled and new materials)

8. Do you use any PAC's/addatives yourself? Which ones?

9. What are the main reasons for using additives? (Physical properties, cost-efficiency, useful during process, etc.)

10. What are the biggest barriers/challenges in using additives?

11. Are there any chemical changes in the process of making the products? (during heating, forming, pressure, etc.)

12. Do you have any problems/challenges with the current process not yet mentioned?

13. What research inputs would be most beneficial/crucial for Plasto at the moment?

B Fourier-tranform infrared spectroscopy

FTIR was used to look for oxidation, but due to time constraints the results were never fully interpreted. Below is a short section on the theory, method used and results of FTIR.

FTIR is the most common and widely used method for determining the composition of microplastics. It is a straightforward and quite reliable method, which is also cheaper and quicker than most other methods, like Py-GC/MS.
The method irradiates a sample with specific wavelengths of infrared light that is close to visible light (750nm-100 000nm), in order to differentiate between plastic and natural materials. The light transmitted at different wavelengths is examined and compared with band patterns to get information about the molecules in the sample. (Crawford & Quinn 2017)

For the measurements, a Bruker ALPHA FTIR spectrometer equipped with an Eco-ATR (attenuated total reflection) sampling module was used. Prior to each sample, a background spectrum was recorded. The transmittance at different wavenumbers can bee seen in Figure 19 below:

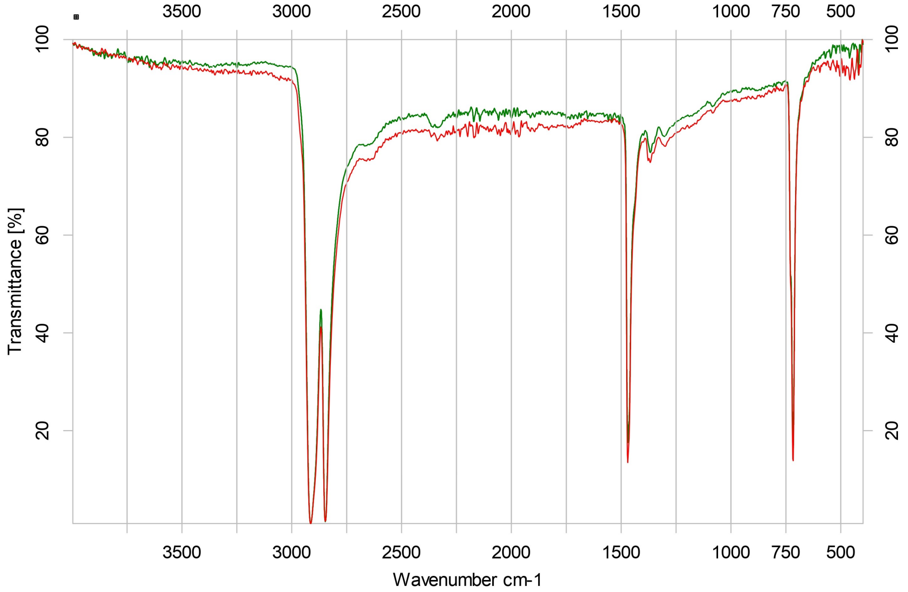


Figure 19: *Results from the ATR-FTIR. Virgin polymer in red, recycled polymer in green.*