PLASTin

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All in for Plastics Recycling

CLIC

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PLASTICS RECYCLING
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Content

PREFACE

Plastics are in many respects versatile and beneficial materials. Their production and consumption has grown constantly, but in the EU only about one-third of plastic waste is recycled. Plastic waste recycling has long been developed by improved separate collection of plastics, mechanical separation of different polymers from the source separated materials, and mechanical recycling of the separated plastics. However, there are many difficulties in the separation of plastics, because the demands of plastic packaging and other products has led to a proliferation of increasingly complex materials, such as multilayer plastics, other materials covered with plastics, and plastics treated with various additives such as flame retardants.

ALL-IN for Plastics Recycling – PLASTin is a recycling project for finding solutions to improve the recycling of plastic materials that are difficult to process. Research and development were carried out to identify brominated flame retardants from plastics of waste electric and electronic equipment (WEEE), and to devise a means of separating them from non-hazardous plastics in WEEE. Another difficult material selected for inclusion in the study was repulping reject of liquid packaging board (LPB), where plastics are contaminated with fibre residues and aluminium foil. Pretreatment and separation methods were researched to enable sustainable mechanical or chemical recycling of these materials. More generally, the PLASTin project generated knowledge about the development of plastic waste material flows, sorting methods for different plastics, the acceptability of recycled plastics by industries and the general public, and the environmental sustainability of various plastics recycling solutions in Finland. The project achieved its objectives, due in large part to the effective collaboration between the research partners and companies involved.

The forecasts made in the project suggest that plastic waste generation in Finland will continue to increase from the current level by about 35% by 2030. However, there have been good developments in packaging design, which aims to reduce the amounts of materials used and improve recyclability. At the national level, recycling of plastics can be made most sustainable by combined methods of increased separate collection, increased capacity of treatment plants, improved yield of recycled plastics from the collected material, and completing mechanical recycling with chemical recycling. The results show that more than half of the climate-related impact of plastic waste can be reduced with a combination of these methods. The consumer survey results show that people generally have a positive attitude towards recycled plastic products, and would like to see an increase in the amount and variety of products made from recycled plastics. The regulatory environment is considered complex, and recycling targets are becoming more demanding. New measures, such as minimum requirements for recycled content, the promotion of recyclability and data transfer issues concerning harmful substances, are being developed and promoted.

The European Union's ambitious targets for plastic waste recycling will not easily be achieved, even in the countries that are currently leading the field in this area. Separate collection of plastic waste needs to be increased and developed, but for a sufficient recovery rate the separation of plastics from mixed residual waste is also needed. The results of the study show that applicable sorting technologies must be more widely adopted and further developed if the yields and purity of different plastic types are to be improved. In addition, chemical recycling processes must be applied and developed for plastic recycling so as to complement mechanical recycling and obtain quality feedstock from difficult plastic waste fractions as well. One way to improve the collection rates for plastics in sparsely populated areas is collection of plastics that are comingled with other recyclables. The life cycle assessment showed that it is possible to reduce the environmental impacts of plastic, cardboard and metal waste, using comingled collection, by more than 60% compared to regional collection of these recyclables.

A fast-growing packaging material, liquid packaging board (LPB) is quite commonly recycled by separating the fibres from plastic and aluminium coverings in a repulping process. The repulping reject contains between 42 and 75% plastic, with the remainder consisting of fibre residues and aluminium. From this residue it is quite easy to separate high-density polyethylene (HDPE) plastic caps and necks for recycling. The repulping reject was tested with and without pretreatment (separation of some of the fibre and aluminium residues) with a number of methods. The test samples were processable with common melt processing techniques such as extrusion, injection moulding and rotational moulding. Compared to the commercial wood plastic composites, the mechanical properties of the compounds were slightly lower in terms of stiffness and strength, but the properties could be modified by adjusting the composition. The environmental performance of the recovery of the repulping reject of LPB was studied between incineration, mechanical recycling and chemical recycling. If mechanically recycled plastics can replace at least 30% of virgin plastics, this will have the least global warming impact. However, chemical recycling can also decrease the global warming potential (GWP) of reject recovery by 70% compared to incineration.

Another fast-growing waste material is waste electrical and electronic equipment (WEEE). It contains large amounts of plastics, which are difficult to recycle partly because they contain hazardous additives such as brominated flame retardants (BFR). The PLASTin project involved the study and testing of the potential and performance of Raman hyperspectral imaging technology, active hyperspectral imaging (AHS) and laser-induced breakdown spectroscopy (LIBS) for quantifying the elemental bromine concentration in WEEE plastics. Raman hyperspectral imaging and AHS can be used to identify high-bromine samples from low-bromine ones, although with a relatively high threshold, whereas LIBS is very accurate in quantifying the concentration level. A commercial separation line based on X-ray fluorescence (XRF) spectroscopy was also tested for separating bromine-rich and bromine-poor WEEE plastics from each other. The results were very positive: chemical analysis did not practically find bromine from the separated bromine-poor plastics. After separating these plastics into different grades, they were injection- moulded and tested. Their mechanical properties compared well with virgin plastics, and they are therefore suitable for many different uses. The environmental impacts of WEEE recycling after separation of brominated plastics were compared to the current energy recovery using a life cycle assessment. Mechanical recycling has the lowest GWP impact if the recycled plastics can adequately substitute virgin plastics. Chemical recycling can also decrease the GWP impact by about 40%, although the yield of plastic products by pyrolysis seems rather low.

Professor **Mika Horttanainen**, LUT University
Scientific Director of PLASTin

Tiina Malin, Kuusakoski Oy
R&D Manager
Chairman of the PLASTin Steering Group

The PLASTin project in brief

PLASTin in numbers

Duration .... 1 March 2020 – 30 June 2022
Budget .... €2.81 million
Company budget .... €1.31 million
Research institution budget .... €1.5 million
Number of persons involved 56
Number of publications 17

Consortium

The ALL-IN for Plastics Recycling – PLASTin project was established to support the plastics industry actors in developing systemic and environmentally optimised recycling concepts.

In the two-year project, the PLASTin partners developed new knowledge of recycling processes and technologies, and system-level understanding, allowing improved business opportunities based on recycling.

PLASTin brought together a wide consortium of operators in the plastics ecosystem. The consortium consisted of four industry core partners with own parallel project, and five research institutes responsible for high-level scientific research. In addition, five collaborative partners contributed to the project implementation.

Figure 1. PLASTin project consortium

Industry core partners

- BMH Technology Oy
- Borealis Polymers Oy
- Fortum Waste Solutions Oy
- Kuusakoski Oy

Research institutes

- Arcada University of Applied Sciences (Arcada)
- Finnish Environment Institute (SYKE)
- LUT University
- Tampere University
- Technical Research Centre of Finland (VTT)

Collaborative partners

- Griffin Refineries Oy
- Muovipoli
- Neste Corporation
- Rosk'n Roll Oy Ab
- Suomen Uusiomuovi Oy

Program management

The project was coordinated by a steering group and three teams, each operating with their own theme. The steering group consisted of representatives of the project partners and expert members. Its main function was to oversee the overall management of the project.

The research activities were organised around three main research themes that spanned the whole ecosystem: Market System and Shaping, Recycling Tomorrow, and Recycling of Difficult Plastic Fractions.

The Market System and Shaping theme focused on assessing future recovered plastic waste flows considering foreseeable changes in the operating environment. The Recycling Tomorrow theme provided information on the economically and environmentally optimal collection and pre-treatment concepts, systems and technologies. In the Recycling of Difficult Plastic Fractions theme, the focus was on economical ways to recycle multilayer plastics, such as liquid packaging board plastics, and plastics from WEEE. The three research areas were led by industry leaders, supported by secretaries from the research institutes.

The scientific director of the project was Professor Mika Horttanainen of LUT University. Tiina Malin, Kuusakoski Oy chaired the Steering group. The project coordination was contracted from CLIC Innovation Oy, and Pirjo Kaivos was appointed project coordinator.

Chairs and secretaries of the project		
	Chair/industry leader	Secretary
Steering group	Tiina Malin, Kuusakoski Oy	Pirjo Kaivos, CLIC Innovation
Market System and Shaping	Reetta Anderson, Fortum Waste Solutions Oy	Susanna Horn, SYKE
Recycling Tomorrow	Auli Nummila-Pakarinen, Borealis Polymers Oy	Mona Arnold, VTT
Recycling of Difficult Plastic Fractions	Tiina Malin, Kuusakoski Oy	Ilari Jönkkäri, Tampere University

PLASTin Steering Group

Tiina Malin, Kuusakoski Oy, Chairman
Reetta Anderson, Fortum Waste Solutions Oy
Anne Fraser-Vatto, Griffin Refineries Oy
Vesa Heikkonen, Rosk'n Roll Oy Ab
Jarmo Kela, Neste Oyj
Auli Nummila-Pakarinen, Borealis Polymers Oy
Peter Wallenius, BMH Oy
Dr. Mirja Andersson, Arcada University of Applied Sciences
Prof. Mika Horttanainen, LUT University
Dr. Sari Kauppi, Finnish Environment Institute
Dr. Ilari Jönkkäri, Tampere University
Eetta Saarimäki, VTT Technical Research Centre of Finland

Expert members

Sauli Eerola, Muovipoli Oy
Pirjo Kaivos, CLIC Innovation Oy, Secretary
Taina Kujanpää, CLIC Innovation
Peter Rasmussen, Finnish Plastics Recycling Ltd
Sisko Sipilä, Business Finland
Sampo Tukiainen, Tukiainen, Business Finland

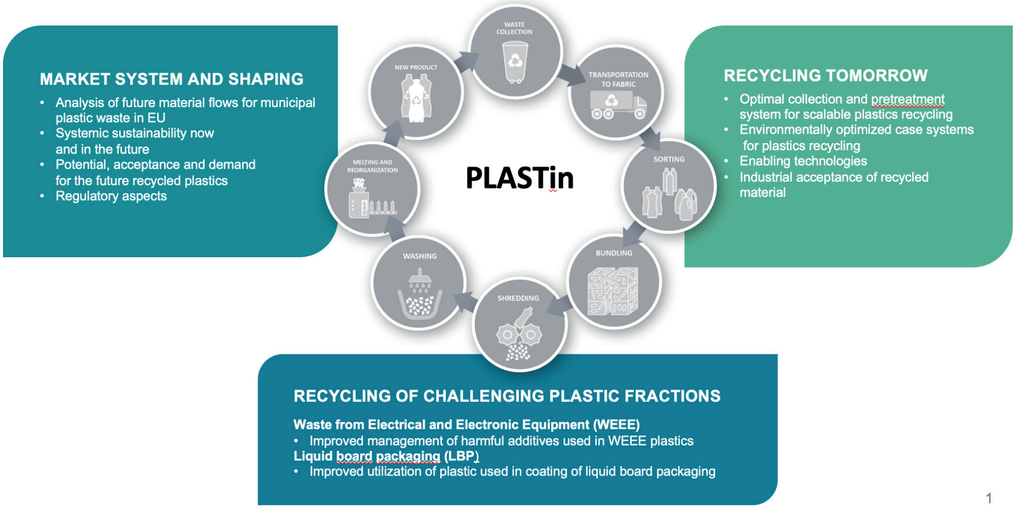

Figure 2. Project structure

RESEARCH THEME 1

MARKET SYSTEM AND SHAPING

The plastic waste markets are undergoing changes within Finland, the EU and globally. There are several reasons for these transformations, including the changing material quantities and qualities, the introduction of new products and materials, stricter policies and regulations, novel processing technologies, and increasing demands from stakeholders. These changes will ultimately affect the sustainability of the waste processing system, and of other linked sectors such as energy provision or substitute material providers. To support decision-making for various actors and increase awareness of the potential effects of these decisions, the aim of this project was to study multiple aspects of the current plastic waste markets and how they will be shaped in the future.

To gain an overview of the waste management system as it currently stands and of the possible future scenarios for its performance, several perspectives must be considered. There were four closely linked, mutually supportive tasks, which all look at the plastic material markets from different viewpoints: from the policy and regulatory perspective; from the consumer perspective, based on behaviour, attitudes and demand; from the market perspective, based on volumes and qualities of plastic packaging; and from the perspective of the overall environmental sustainability of the system (Figure 3). The tasks were carried out using multiple methods and datasets, such as expert interviews, literature reviews, national-scale consumer surveys and statistics, life cycle modelling, market studies and policy analyses.

Figure 3. WP1 considers multiple aspects and their interlinkages

In general, the results point towards a continuing increase in the use of plastic packaging, and thus an increased need to manage the full life cycles of different plastic waste fractions, including a carbon-efficient, environmentally sustainable end-of-life phase. Although the demand for plastic packaging will continue to grow, the regulatory framework is still volatile and the Finnish recycling system has reached its limit in terms of capacity. However, several positive changes are visible in the current operating system. In addition to being driven by considerations related to functionality and cost, packaging design is also increasingly driven by environmental considerations, and consumer preferences for recycled plastic products in Finland seem positive. Moreover, new investments are expected in mechanical and chemical recycling and in energy recovery, which will provide a range of processing options for various waste fractions and sufficient capacities. This will in turn clearly reduce the carbon impacts of the entire plastic waste processing system. The regulatory uncertainty may be tackled not only by closely following the ongoing changes, but also by making use of the possibilities to influence them, such as eco-design requirements and eco-modulation in particular. This involves imposing penalties for the use of materials that are less environmentally friendly, and rewarding the use of less environmentally harmful materials.

In sum, the project provided ample insight into the various factors that need to be considered when deciding on future policies, planning for investments, raising consumer awareness and requiring sustainability to be taken into account in these processes.

The key results indicate that:

- Plastic packaging waste generated in Finnish households and the public service sector is estimated to increase by about 35% by 2030. Polyethene and polypropylene are the most widely used polymers in the packaging industry, and their usage is expected to increase further. Although the demand for plastic packaging will continue to grow, packaging is getting lighter and thinner. Packaging design is driven by functionality and cost, and to an increasing extent also by considerations related to environmental sustainability.

- Rather than introducing stand-alone modifications, the combined implementation of various changes to the plastics recycling system (e.g. increased recycling capacity, increased recycling yield increased collection, introduction of chemical recycling) is most effective from a climate perspective, as some of these modifications are mutually reinforcing. In total, a 30% reduction in climate-related impacts can be achieved if all the aforementioned changes are implemented consecutively.

- Consumer preferences for recycled plastic products in Finland seem positive. The respondents were active in recycling plastic packaging, and most were satisfied with the acquired products. Many complained that there are too few products available that are made from recycled plastics, and stated that the use of recycled plastic increases the attractiveness of products. Based on their comments, more attention should be paid to availability and product selection, safety, labelling and providing information about recycled plastics.

- The regulatory framework for the management of plastics is rapidly changing and will most likely continue to do so, creating uncertainty within the plastics industry and making it a less attractive target for investments. Keeping up with rapidly changing requirements, seizing the opportunity to shape future requirements, promoting recyclability, and building up product data transfer are some of the general recommendations for industry actors.

GENERATION OF MUNICIPAL PLASTIC WASTE

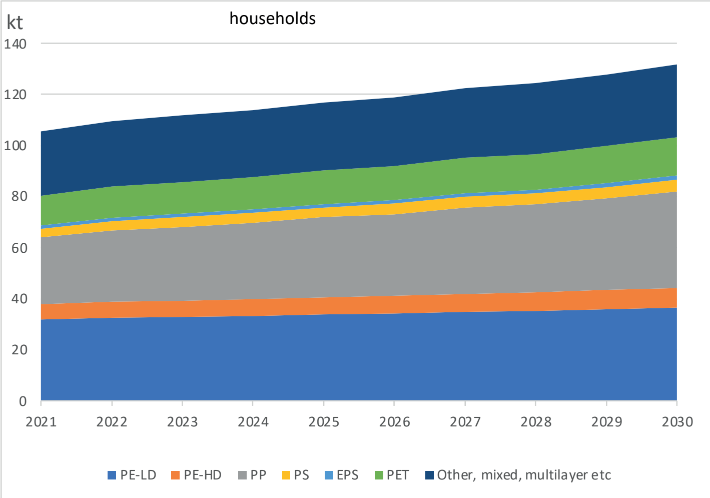

Figure 4. Outlook of plastic packaging waste flows in Finland, generated by households

Description

The plastic waste markets are undergoing major changes, as are the ways in which plastic products are designed, used, and recycled in the EU. This section looks at how economic and technological factors will change the material flows in terms of both with quality and quantity. The analysis concentrates on the EU overall, with particular emphasis on Finland. The current collection and management system in Europe's main plastic consuming countries (France, Germany and Poland) is also taken into account for solutions for plastic waste processing in the United Arab Emirates. The research report also discusses trends and factors that affect the quality and quantity of future plastic packaging waste.

Results

Plastic packaging waste generated in Finnish households and the (public) service sector, both of which are mostly collected by municipal waste organisations, was estimated at around 112,000 tonnes in 2020. The amount is estimated to increase by about 35% by 2030. The same growth rate was used for plastic packaging waste generated by households, with the baseline for 2020 being 102,000 tonnes. Polyethene and polypropylene are the most used polymers in the packaging industry. The amount of PE in all packaging is over one-third, and PP accounts for approximately a quarter. The proportions of PE, HD and PP are also forecasted to increase. The estimation is based on available statistics, public research and market studies, all of which indicate a continuing increase in the use of plastic packaging and thus an increased need to manage the end-of-life phase of waste generation. The statement was also backed by the responses to an e-Delphi survey and a Survey Monkey survey, which were administered to approximately 90 Finnish and international experts in plastics production and waste management.

France, Germany and Poland are among the six countries generating the largest volumes of plastic waste in Europe (Plastic Europe 2020). Although Germany has a long tradition in comingled collection of recyclates from households, less than 50 % is collected through the system and the actually recycled share has been estimated to 38 % The main reason for the discrepancy is wrongly sorted or collected waste, which is a problem especially in big cities. In France used plastic packaging is collected separately in only part of the country. However, France has also been in the forefront in banning certain single-use plastics products. This ban was lifted in connection with the societal measures taken to combat the COVID-19 pandemic. Poland has recently started providing separate collection for plastics and other recyclates, and provides fiscal incentives for property owners. However, enforcement has not yet been followed up.

The main strategy in the United Arab Emirates for solving problems related to diverting waste from landfills is focusing on waste-to-energy solutions for collected household waste. Waste is not separated into material or product fractions at the source.

Although the demand for plastic packaging will continue to grow, packaging is getting lighter and thinner. Packaging design is driven by functionality and cost, and to an increasing extent also by considerations related to environmental sustainability. Important drivers for packaging design are the commitment of large corporations to sustainability and new directives or regulations relating to plastics waste management, single-use plastics and local waste collection systems. The aforementioned corporate commitment is largely driven by consumer behaviour and the preferences of end users. Although multilayer flexibles are still often difficult to process in terms of current end-of life management, a high product-to-packaging ratio, low volume of generated waste, and less energy consumption for manufacturing are some of the several advantages of multilayer flexible packaging over rigid packaging solutions. Moreover, chemical recycling, which is now progressing towards market readiness, may provide an end-of-life solution for handling such plastic packaging waste. Recent investment decisions regarding chemical recycling plants in Europe may also contribute to this.

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CLIMATE IMPACTS OF PLASTIC PACKAGING WASTE MANAGEMENT IN FINLAND – A SCENARIO ANALYSIS

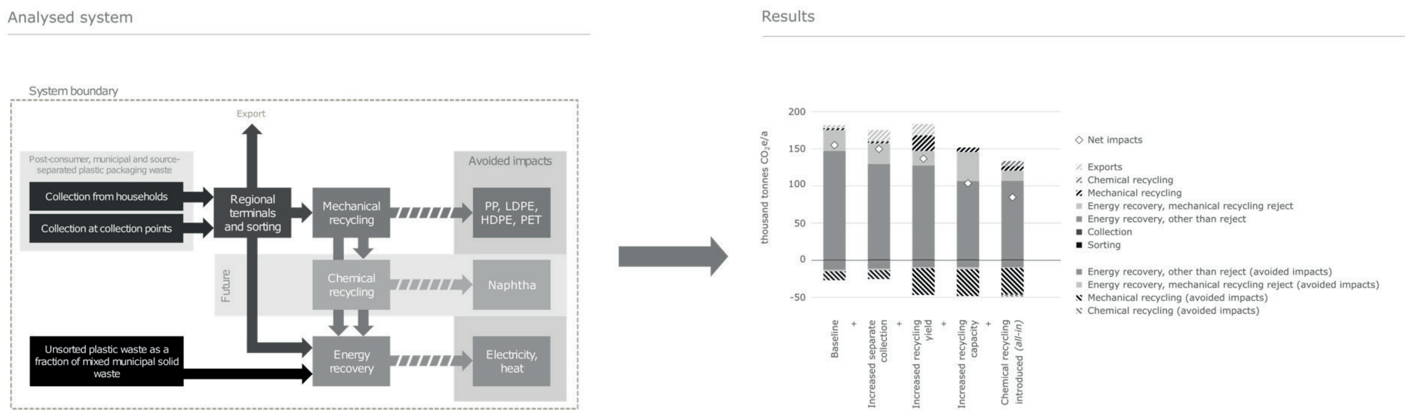

Figure 5. Outlook of plastic packaging waste flows in Finland, generated by households

With more stringent policies and regulations in the EU as a whole as well as in Finland, the plastic waste system will require system-level changes to become financially and environmentally sustainable. Reaching the EU-level plastic waste targets may not only be regarded as a compulsory inconvenience, but as a possibility to prepare for the future and create an optimised, more sustainable waste management system. For example, plans have been made to increase waste collection rates. However, new high-yield mechanical recycling facilities need to be built concurrently to increase the processing capacity. Plans have also been made to include chemical recycling in the recycling technology mix in order to handle the more difficult fractions. Sorting capability needs to be improved to ensure optimal feedstock for each recycling process. The outputs from recycling must be of good quality to substitute for a large variety of primary materials, and to serve an established secondary market. With all these options improving the waste management system, it is necessary to assess the environmental benefits of individual measures compared to the current situation, as combinations of these measures. Since these are changes related to the future and the waste flows with related process emissions remain highly uncertain, the uncertainty of each change needs to be thoroughly examined. Furthermore, in order to facilitate sustainable decision-making these cause-and-effect loops need to be clearly communicated to all actors within the value chain.

The purposes of this research were to study the current Finnish national system of post-consumer plastic packaging waste management and to quantify its climate-related impacts, to explore a set of alternative and future scenarios and their potential climate-related impacts, and to provide insights for policymaking regarding future plastic waste management. For this reason, the various routes for collecting, storing, sorting, and processing of plastic waste were estimated based on a prospective material flow assessment (MFA). Based on this, the climate-related impacts of the entire system were estimated using a life cycle assessment. The climate-related impacts of the current practices were compared with possible future scenarios to support decision-making. The explorative part of the study, including the scenarios assessment and sensitivity analysis, is intended to deepen stakeholders' understanding of the complexities of interpreting the results of system assessment of this kind.

The climate-related impacts of the post-consumer plastic packaging waste processing system in Finland in 2019 were 178 kt CO2e, excluding exports and credits from avoided production and including only the current mechanical recycling capacity. Including exports, the total impacts were 182 kt CO2e. The contribution of exports, energy recovery and mechanical recycling are 2.3%, 95.7% and 1.5%, respectively. The remaining 0.5% is attributed to collection and sorting. When avoided production is included in the equation, the net climate impacts of the system are 155 kt CO2e, or 151 kt CO2e if export is excluded. The impacts allocated per tonne of generated waste are 2.3 t CO2e/t when export is excluded, 2.4 t CO2e/t when export is included, 1.9 t CO2e/t for net impacts without export, and 2 t CO2e/t for net impacts with export.

The scenarios were studied both in isolation and as a sequenced combination of scenarios. In isolation, the individual scenarios lead to a reduction of between 2.2 and 11.2% in the net climate impacts (increased collection –3.3%, increased recycling yield -9.4%, increased recycling capacity -2.2%, introduction of chemical recycling -11.2%). The scenarios present chemical recycling as the single most beneficial modification to the system. A combination of the scenarios leads to a total reduction of 45.4% in net climate impacts. The combined implementation of various improvements is therefore more effective, as some of these modifications are mutually reinforcing. Figure 5 shows a logical sequence of the cumulative implementation of different measures. The results illustrate how adding more measures creates synergies and effectively decreases impacts.

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Publications

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CONSUMER PREFERENCES FOR RECYCLED PLASTICS: OBSERVATIONS FROM A CITIZEN SURVEY

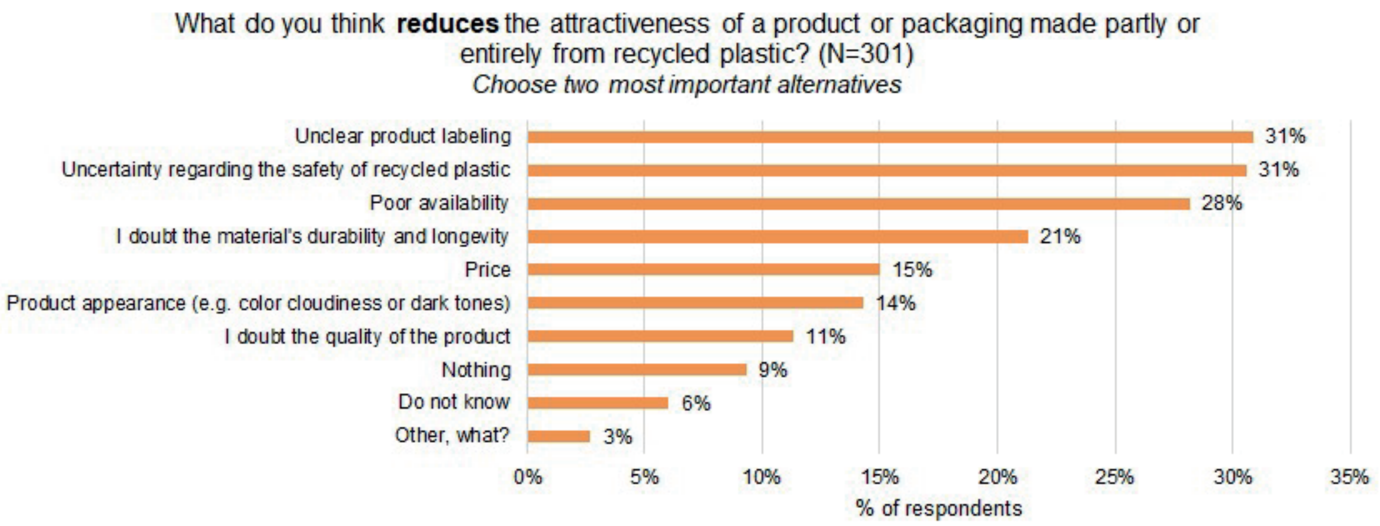

Figure 6. Factors that the respondents felt reduced the attractiveness of a product or packaging made of recycled plastic

So far, the literature on consumer preferences for recycled plastic products is limited. Previous studies have focused on plastic pollution (Magnier et al. 2019), biobased plastics (e.g. Scherer et al. 2018; Zwicker et al. 2021), and from products especially on bottles (De Marchi et al. 2020; Orset et al. 2017). The aim of this task is to study consumer preferences for products made of recycled plastics. In addition, the task explores factors that are linked to the consumption behaviour and consumer attitudes.

To examine these, a consumer survey was conducted in May and June of 2021. Survey participants were recruited by email, and the survey was conducted online. The survey invitations were sent to 5,000 Finnish residents between the ages of 18 and 80. The participants were randomly drawn from the Finnish Population Information System. The survey received 301 responses (6% response rate). The response rate is rather low, and thus the collected sample may suffer from nonresponse bias.

The survey results indicated that respondents were active on recycling plastic packaging, as only 20% of them rarely or never recycled their plastic packaging waste. The common factor for recycling and not recycling related to the accessibility of plastic packaging waste collection points. Among other motivational factors to recycle are sense of duty, concern for the environment, and the belief that materials should be recycled.

Nearly 60% of the respondents owned or had owned a product made partly or fully of recycled plastics. There were also many respondents (31%) who did not know for sure whether they had owned such products. Of those who had owned for sure, majority had owned plastic bags (67%), cleaning equipment (44%) and storage supplies (32%). When asking how the usage of recycled plastic had affected the purchase decision, 41% stated that it had had a somewhat positive effect, and 45%judged the effect to be very positive. Only 1% of respondents found there to be negative effects.

The analysis of the responses included investigation of the factors explaining respondents' answers to a question about whether a product is more attractive if the plastic it contains is recycled. The analysis revealed that females, younger people, those who recycle, and people who consider themselves to be environmentally conscious are likelier to think that the use of recycled plastics increases the attractiveness. Individuals who place more importance on the appearance of products are less likely to share this view. Income level, living in an urban area, or self-evaluated level of knowledge about plastics were not statistically relevant to explaining this view.

Figure 6 presents common factors that may reduce the attractiveness of products made with recycled plastics. Around one-third of respondents (31%) stated that the labelling of such products is unclear. Roughly one-third of respondents had some doubts about the safety of the material, and one-third thought that the poor availability of such plastics reduces their attractiveness. Just over 20% doubted the durability of the material, and 14% thought the appearance decreases the attractiveness. On the other hand, when asked about what increases the attractiveness of products made of recycled plastics, the respondents particularly valued the re-use of materials and lower environmental footprints.

As recycled plastics can have a characteristic colour and texture, the survey studied what the respondents thought about these likely deviations. The main finding was that people are most willing to accept colour deviations, and that surface deviations were also relatively well accepted. Less common deviations in smell were not as widely accepted as deviations in colour or surface texture.

The survey also gathered information on suitable applications for recycled plastics. Respondents stated that recycled plastics suite for many already existing products (e.g. bags and packaging, gardening, cleaning and storage equipment, construction products, and textiles). Some respondents considered the use of recycled plastic in a product to be positive in almost every context.

Examples of information that respondents would like to find on products made of recycled plastic include labels indicating the use of recycled plastics, and preferably the amount of it in the product, an indication of the recyclability of the product, sorting instructions, and information on the related environmental impact compared to virgin plastics. Furthermore, 85% of respondents indicated that a label for recycled plastics would increase interest in buying the product.

Overall, consumer preferences in Finland for recycled plastic products seem positive. Developers and producers of consumer recycled plastic products should pay attention to availability and product selection, safety, labelling and adding information on recycled plastics.

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BENEFITS FOR PARTICIPANTS

BMH TECHNOLOGY

BMH Fuel to Feedstock accelerates new business creation

BMH Technology is a Finnish technology and project company that creates demanding material handling systems and industrial-scale waste refining solutions.

Our mission is to create solutions for using waste to produce raw materials and renewable energy.

In the BMH Fuel to Feedstock project, we created new information and concepts to advance our growth strategy. We can build on the PLASTin research project results to accelerate innovation in the Waste to Chemicals business segment. We will also benefit from the new knowledge of the markets and customer requirements that was gained with our PLASTin partners.

BMH Technology Oy, **Ville Hakanperä,** VP, Technology

IDENTIFIED REGULATORY CHALLENGES FACING PLASTICS RECYCLING AND PROPOSALS FOR ACTION

The regulatory framework governing plastic, plastic products and their recovery significantly affects the life cycle of plastic materials. To gain a better understanding of the regulatory environment affecting plastics recycling, representatives of each task within the PLASTin project were interviewed. Based on the interviews, the most relevant themes related to regulation were identified, and ways to address these problems were discussed. Recommendations were made based on previous research and were discussed with PLASTin partners. The recommendations to promote the recovery of plastic wastes were then finalised.

The regulatory framework for the management of plastics is rapidly changing, and will most likely continue to do so. This creates uncertainty within the plastics industry and makes it less attractive to potential investors. Nevertheless, it is clear that the recycling targets for plastic waste are becoming more demanding, and this can be seen in the recent amendments to EU waste and packaging legislation. The amendments to the recycling target and their calculation methods will negatively affect the calculated recovery rates of EU member states. The amendments will require intensified efforts to rapidly increase recycling rates in Finland. This creates a need for quick responses from the plastics industry.

Despite this, the new legal provisions and the complexity of plastic products do not provide optimal conditions for the improvement of material cycles within the industry. The regulatory environment for plastics recycling is often considered complex and confusing. Moreover, it is frequently argued that the existing legislation related to plastics does not promote efficient recycling of them. Among other things, complex product design and harmful additives often diminish the potential for recycling plastic wastes. More efficient recovery of plastics could also be promoted through regulation of product design, either through a eco-design framework or through eco-modulation aspect within the existing extended producer responsibility schemes.

Demand for recycled plastics will be created with new instruments such as minimum requirements for recycled plastic content for different product groups. This kind of requirement for PET bottles has already been enacted in the European Union directive on single-use plastics (Directive (EU) 2019/904). However, these provisions merely create demand for recycled plastics – they will not solve the problems faced by recyclers.

Some key regulatory difficulties concerning plastics recycling were identified above. Below we offer general and regulation-specific recommendations for industry actors on how to operate in this constantly altering environment and reach the shifting recycling targets.

General recommendations for the industry:

The changing regulatory environment and more stringent requirements for recycling create opportunities for business, but **attention must be paid to keeping up with rapidly changing requirements.** This includes keeping track of public provisions and the development of private regulatory actions, such as standards and voluntary commitments.

Regulatory change of eco-design requirements for circularity, and rule-making for eco-modulation in particular, opens up **possibilities to influence how the requirements are formulated,** although these opportunities are typically available only to the most resourceful companies. Attempting to influence the development of new regulations in the drafting phase is typically a more effective strategy than opposing them. (Kautto 2009)

Recyclability is likely to be promoted as an eco-modulation goal in various member states, and the related designing will presumably be profitable.

Harmful additives often diminish the potential for recycling. **There will be increasing demand for technological and methodological development for data transfer** regarding the composition of plastic products, their origin, previous use, recycling information and **identification of substances** in different matrices. (Kauppi et al. 2019)

Regulation-specific recommendations for industry actors:

Follow EU rulings, for example on the interpretation of the EU directive on single-use plastics (directive (EU) 2019/904), and on the chemical recycling of plastics. The interpretations of key concepts such as 'plastic', 'single-use plastic product' and 'recycling' in the context of chemical recycling play a crucial role in the regulatory framework for plastic products and the recovery of plastics. Having alternative action plans for different possible outcomes of these rulings and preparing for the 'worst-case scenario' increases the resilience of business operations.

Follow on-going national regulatory action. A national end-of-waste decree is being drafted for mechanically recycled plastics. In addition, further guidance for case-by-case end-of-waste decision-making is expected after the enactment of the amendments to the national Waste Act.

Prepare for the mandatory provision of data for eco-modulation. Having more EPR fee subcategories is highly recommended by the Commission to increase incentives for durability, repairability, reusability and recyclability, and for minimising the use of dangerous substances. Additionally, the use of recycled content in products could be facilitated through eco-modulation of fees.

Seek opportunities for using recycled material. Requirements for incorporating 25% of recycled plastic in PET beverage bottles from 2025, and 30% in all plastic beverage bottles from 2030 are already included in the EU directive on single-use plastics. Similar requirements or clear incentives for recycled raw material use are likely to be included in the forthcoming legislation for other end-use sectors as well.

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RESEARCH THEME 2

RECYCLING TOMORROW

The current recycling rate of plastics in Europe is still significantly behind the targets set by the EU for used plastic packaging. Even in countries where separate collection practices are relatively advanced, the recovery rate is less than 30%, and part of the recovered plastic is not actually recycled but is ultimately incinerated or disposed of in landfills. To catch up the gap, technological innovations are needed both with respect to collection and valorisation of the recovered end-of-life plastics. Moreover, for further deployment, it is essential to have a view on the environmental sustainability of the different recycling and recovery methods and systems. Knowledge on the environmental sustainability and key factors affecting it, supports decision-making relating to system solutions and directs the R&D work aiming at effective and sustainable recycling technologies.

Summary, key results and impacts

The survey performed within the PLASTin project and results described in the section of the report on the first research theme indicate that Finnish consumers are open to recycling their plastic packaging waste and choosing products with recycled plastic content. The same study also showed that access to collection points is an important factor in positive attitudes towards recycling.

The research on the second research theme confirmed that even when consumer attitudes are positive and separate collection of plastic packaging waste is implemented, a large amount of it is still found in mixed waste fraction. Many other plastic fractions do not yet have collection systems in place in Finland. Thus, post-sorting from mixed waste streams and comingled collection are additional ways to increase the collection rate of all household plastics waste. Sorting technologies are available and mechanical sorting of waste can be applied.

Collected plastic waste needs to be sorted into uniform fractions for recycling into specific applications. As the collection rate increases, the need for sorting increases accordingly. For overall environmental and economic efficiency, mechanical recycling should be complemented with chemical recycling in order to minimise the incineration of plastics.

Given the current technological and regulatory framework, there is increased need for chemical recycling to provide virgin-quality recycled plastics for food packaging and other applications. With the exception of PET from certified recycling loops, mechanically recycled plastics cannot be used for applications in which the material comes into contact with food.

In sparsely populated areas, comingled collection of different recyclables in a single waste container can bring environmental benefits. A life cycle assessment case study, in which plastics, cardboard and metals (PMC) were collected from properties together, showed a decrease in greenhouse gas emissions of 64% (260 kg CO2 equivalent per tonne of PMC waste). However, the economic feasibility of collection and capacity needs for mechanical sorting requires further examination.

Major advances in recycling can be made when technology is effectively applied and regulation is put in place to promote the shift to circularity in a safe but forward-looking way.

BENEFITS FOR PARTICIPANTS

MUOVIPOLI

Muovipoli Oy is a development, research and material testing company specialising in plastics and plastic products. Muovipoli was established in 1998 as a development centre for the plastics industries in Finland. Its 28 stockholders include both public and private parties, among them industrial companies, universities, development organisations, and the Finnish Plastics Industries Federation (FIPIF). Muovipoli's strengths are in long experience of plastics and production technologies, bioplastics and recycled plastics related innovation processes and broad network ranging from universities to experts. In collaboration with the FIPIF, in 2019 Muovipoli established a New Plastics Center (NPC) to foster market-based biomaterial innovations in collaboration with companies, research organisations and the network.

Muovipoli participated in the PLASTin project as a collaborative company partner, including in the steering group and by providing expert resource input on shaping the market system and no-waste recycling. The main goal of Muovipoli's activities was to integrate the plastics industry, especially the SME companies participating in the project, and the development of the Finnish plastics recycling ecosystem. The activities of Muovipoli supported the work related to the acceptance of difficult recycled plastics in markets and applications, and helped in assessing the future market potential and development of difficult plastics fractions.

The PLASTin project made a significant contribution to developing the Finnish plastics recycling ecosystem by creating new systemic-level, data-based knowledge of recycling concepts, recycling processes and technologies. With system- level understanding, new business and development opportunities for Finnish companies have also been identified. We hope that this work will continue as new joint projects and efforts, offering sustainable growth platforms and impetus for the Finnish plastics and recycling sector in the future.

Muovipoli Oy, **Sauli Eerola**, Managing Director

	Environmental performance		Economic performance	
	Urban	Rural	Urban	Rural
Source separation with kerbside collection	-	--	-	--
Commingled collection	+/-	+/-	+/-	+/-
Centralised post-collection separation	+	+	+	+
Most suitable combination of methods	++	++	++	++

Table 1. Environmental and economic performance of different plastic packaging waste (PPW) collection schemes

Description

The study assesses novel systems technologies contributing to reaching the goal of a 55% recycling rate for plastic packaging waste by 2030, as set by the EU. It examines current and emerging collection and recovery systems for municipal plastic waste, and provides an overview of related costs and environmental impacts.

The research focused on national and regional collection and pre-treatment schemes. The analysis drew on the literature, patent searches, expert interviews and two surveys addressed to Finnish and European experts. The technology advancements are complemented with a synthesis of results from national and regional studies on the economic and environmental sustainability of plastic collection schemes.

Results

To achieve a targeted recycling rate, an efficient collection system is essential. Various collection systems for plastics are applied throughout Europe, based on separation at the source in households (kerbside collection, drop-off centres), comingling with other waste materials, such as metal and paper, or relying on post-separation from mixed waste. In many cases, hybrid models are also applied. Most applied systems are relying on consumers awareness and willingness to sort the waste generated in their home, which has so far resulted in a significant proportion of recyclables being disposed of as mixed waste.

Developments in identification and sorting technologies have supported the rollout of post-collection separation, which has in many cases been claimed to provide a higher separation rate and overall lower installation costs for municipalities and householders (Dijkgraaf and Gradus 2020; Rasmussen 2020). Some research (e.g. Bing et al. 2014, Syversen 2019) indicates that post-separation of plastic from mixed waste results in a higher recovery rate than source separation by households. Although investments in such plants have been made in several countries in Europe (e.g. the Netherlands, Norway and Sweden), results from practical runs are only now being made public. When information on the quality and (mechanical) recyclability of the separated dirty waste is still scarce, the full evaluation of the sustainability of such systems remains to be done.

The use of kerbside waste bins equipped with sensor technology is so far limited. Commercially mature systems typically indicate the need to empty the bin remotely, and by that bring about cost and environmental savings through IoT-enabled optimised routing. However, systems able to directly separate the waste into different recyclables have yet not reached the commercial phase.

Current literature and expert interviews do not clearly support a certain plastic waste collection system or technology for meeting the the recovery and recycling target for 2030. Comparing various applied collection and sorting systems applied in Europe, no system for the recovery of post-consumer plastic waste stands out as having a clearly lower environmental impact and minimal cost (Table 1). However, the situation is quite dynamic both in Europe and the US, and political commitments and new regulations have triggered a significant market pull for improved collection and sorting technologies and more advanced recycling methods. Technology development is likely to reduce both the economic and environmental impact of advanced plastic waste management in the next 5 to 10 years.

Automatic post-separation of mixed waste has reached commercial maturity, and it is likely that in the coming years there will be more full-scale plants in operation in Europe, either as a single solution or complementing source separation in households. The advantages are less need to invest in kerbside collection systems for households and the necessary logistics accordingly. Latest results also indicate its beneficial impact on increased recovery rate and climate mitigation potential, the latter through minimising the amount of fossil plastic being disposed of as waste for incineration in energy plants (Eriksson 2021). However, there are still doubts on the cleanliness of the separated plastics, which can impede mechanical recycling. The development of chemical plastics recycling can fill that gap.

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ENVIRONMENTAL SUSTAINABILITY OF COMINGLED COLLECTION COMPARED TO MONO-MATERIAL COLLECTION OF PLASTIC PACKAGING

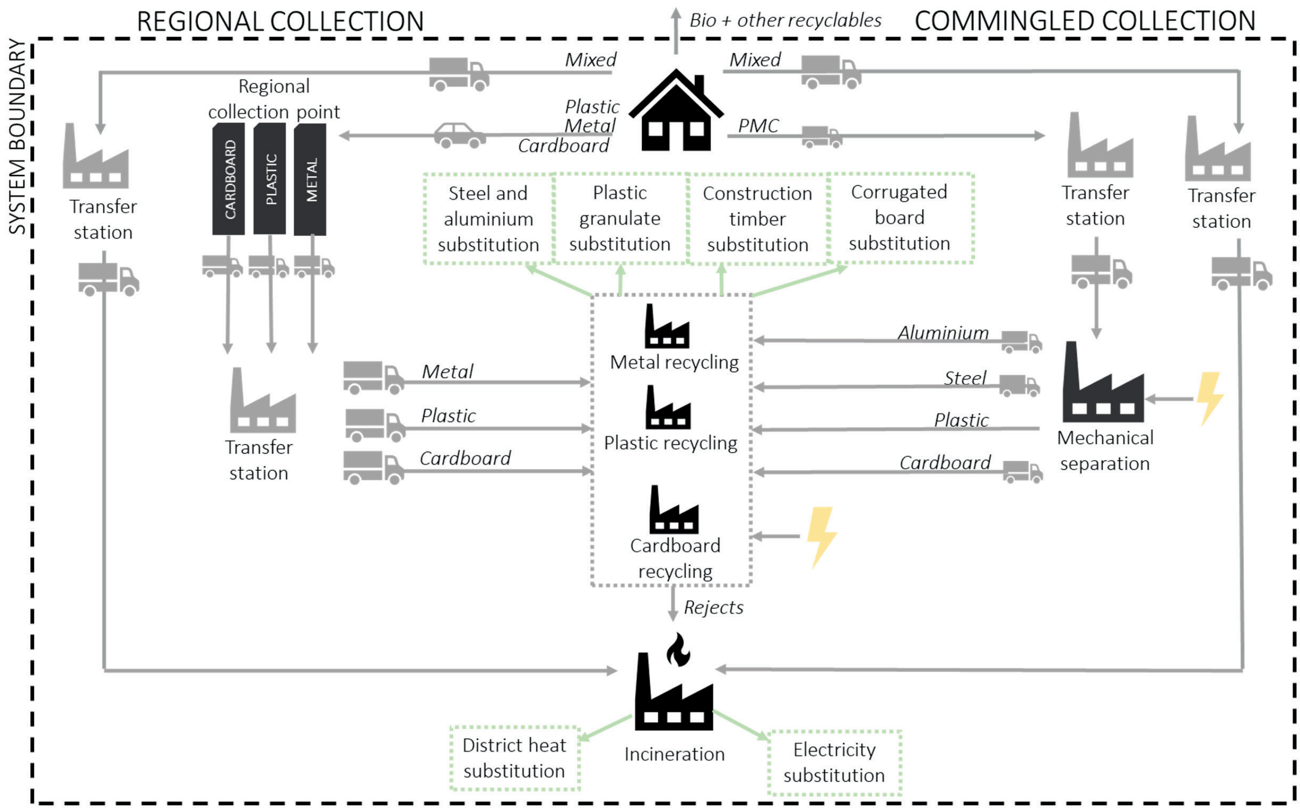

Figure 7. System boundary for regional and comingled collection of plastic, metal and cardboard waste from household.

Description

The plastic packaging recycling target in the EU is 50% by 2025 and 55% by 2030 (Directive 94/62/EC). In Finland, the recycling rate was 42% in 2019 (Pirkanmaa Centre for Economic Development, Transport and the Environment, 2020), which means there is significant room for improvement. As of 2023, it will be required by law in Finland to enable separate collection of plastic in properties with more than five apartments. This law will not apply to detached houses. Residents in sparsely populated regions are expected to take the source separated plastics to regional collection points. The comingled collection of plastic waste with other recyclable fractions such as cardboard and metal directly from households could increase the recycling of these materials, but there is also a need to estimate the impact on environmental performance. To this end, the climate change impact of current regional collection system and an alternative comingled collection system were compared using a functional unit of 1 tonne of generated plastic, metal, and cardboard (PMC) waste. The uncollected PMC waste was assumed to be directed to energy recovery along with mixed residual MSW. The Figure 7 presents the studied systems with the included processes and system boundary. The used life cycle inventory data and detailed descriptions of the studied system can be found in Salmi (2022).

Results

Figure 8 presents the climate-related impact per functional unit from the studied regional collection system (REG) and comingled collection (COM). According to the results, a comingled collection performed better in terms of reducing carbon dioxide equivalent emissions, with a reduction of 50% compared to regional collection of PMC waste. The greatest impact in both scenarios is caused by the incineration of the PMC waste directed to waste-to-energy treatment along with mixed MSW. The transportation emissions also play a significant role and are higher in the regional collection due to the conservative assumption of including the passenger car transport of waste from households to a regional collection centre. However, even if these emissions were not included, the comingled collection system would perform better, having a 38% lower impact than a regional collection system. Another observation from the results is that plastic waste and metal waste treatment have negative net emissions when considering the material substitution, whereas cardboard recycling has a positive impact. This suggests that the material and energy substitutions

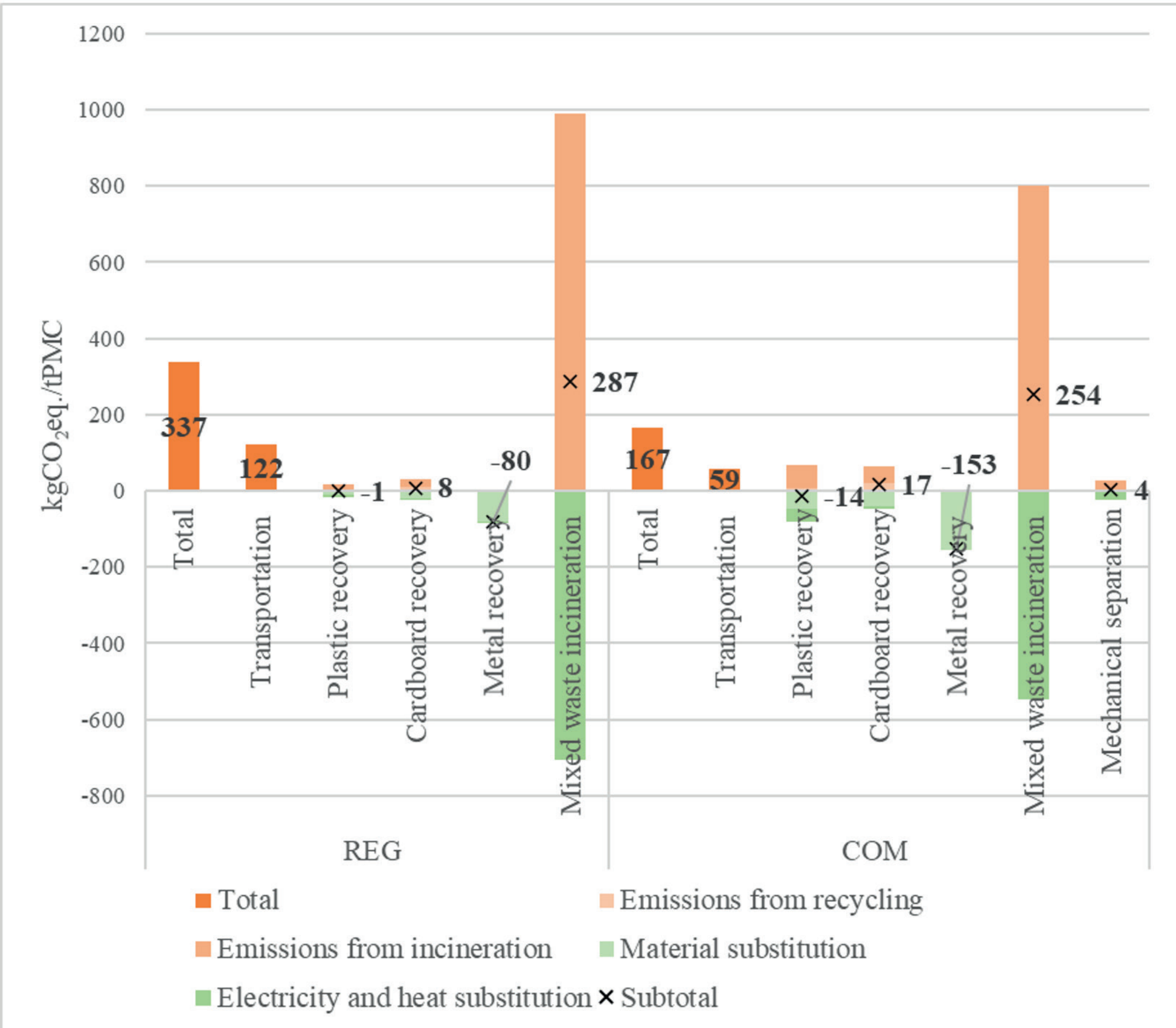

Figure 8. Climate change-related impact results of regional collection (REG) and comingled collection (COM) of plastic, cardboard and metal waste from sparsely populated regions.

are lower than the emissions from incineration and energy consumption.

Based on these results the comingled collection system could outperform the regional collection system from the perspective of the impact on climate change. This would require additional facilities where comingled waste could be separated, and it is uncertain if the generated waste flows from sparsely collected regions could make this financially feasible. It is also uncertain how far the waste would be needed to be transported to achieve a sufficiently high volume of waste material. Additionally, the purity of this source-separated comingled waste in comparison to waste collected from regional collection points is not known. Additional considerations and perhaps pilot trials would be needed to determine these factors.

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FORTUM WASTE SOLUTIONS OY

Fortum Recycling and Waste offers sustainable solutions for the circulation of valuable materials such as plastics, metals, batteries, ashes and slags. Fortum is recycling post-consumer plastic waste and producing Fortum Circo, sustainable and versatile recycled plastic granulates, which can be used as a raw material substitute for virgin plastics. Our plastic refinery concept is unique and designed to ensure the quality of the end product. By keeping the whole recycling process in-house, from sorting, washing, drying and compounding, we can guarantee efficiency and sustainability throughout the production process. With our plastics recycling solution, we are turning waste into a valuable new raw material that can be used for a wide variety of applications and compounds for specific customer needs.

“We joined the PLASTin project because we thought it important to take part in research on recycling plastics fractions that are especially difficult to recycle with existing technologies. Liquid board packaging is a very good example of multilayer material, from which the first recycling phase creates a multi-material reject that is difficult to recycle into a usable material. Removal of harmful substances from the material cycles has been one of the company’s main targets for several decades. For this reason, we were very interested in following the recent studies on the identification and management of the hazardous contaminants in WEEE plastics.

As the project studies dealing with climate-related impact evaluations demonstrate, every possible measure must be taken to reach the climate targets. Our company’s aim is to increase mechanical recycling of plastics as much as is economically viable. Chemical recycling for the mechanical recycling rejects offers a needed addition for recycling rates, when it will be used for producing new materials.

Now that the project has come to an end, we can clearly see how the predictions for future scenarios, sustainability evaluations and research results on consumer opinion support the views that lie behind our own plastics recycling strategy. In addition, more stringent legislation benefits the recycling business, and future incentives such as recycled plastic content requirements for new product groups and eco-modulation will improve the recyclability of plastic packaging.”

Fortum Recycling and Waste, **Reetta Anderson**, R&D Project Manager

ENABLING TECHNOLOGIES FOR PRE-SORTING AND PRE-TREATMENT OF PLASTICS

Description

Accurate and scalable sorting of plastics is a key step in recycling, as it enables the reprocessing of post-consumer plastic waste into high-quality polymers for use in making new plastic products. Around Europe, a number of different collection and sorting systems are used, which all require their own sorting and separation processes (for example, a regional collection scheme can be used, see Figure 7) leading into varying technology requirements. In Finland, source-separated plastic waste from centralised municipal collection points and collection bins in housing companies are directed to the Fortum Waste Solutions' plastic refinery in Riihimäki, which is an industrial-scale reprocessing facility that sorts all the post-consumer waste in Finland.

Sorting technologies need to be improved in order to increase the capacity and accuracy of sorting facilities, and to enable the sorting of present and future difficult plastic fractions. Industrial scale sorting of different plastic polymers is usually accomplished using optical sorting units containing 1) a near-infrared (NIR) spectrometer that scans waste plastics on a conveyor belt; 2) a pneumatic air sorter that is activated by a spectral recognition algorithm, either ejecting the object corresponding to the target polymer or rejecting it.

NIR spectroscopy was found to present several difficulties:

- dark plastics (dyed with carbon black)
- multilayer materials
- overlapping objects
- incapable of accurately sorting high-density polyethylene (HDPE) or low-density polyethylene (LDPE).

Several alternatives to NIR spectroscopy that may overcome its limitations are enumerated in Table 2.

The pneumatic separator also factors in sorting performance:

- overlapping objects may get ejected or rejected together
- material density and the speed of the conveyor belt affect the performance.

Based on the PLASTin research survey, the performance of the sorting facilities has not been extensively studied. This is necessary to identify the best waste collection and sorting system practices. Moreover, it seems no studies have been conducted to accurately determine why a single object is either ejected or rejected – that is, in which case the sensor-based recognition step or the air separator is at fault.

Looking at the future of plastic sorting, there are various difficulties to be solved with new technologies. The review of current post-consumer plastic packaging recycling solutions revealed a fragmented market, with a large variety of different operating schemes and technology combinations. In the near future, the plastics recycling industry should be able to enhance the plastic waste collection and recycling process to meet the quantity targets set by European legislation. At the same time, the sorting and recycling processes should be improved to provide high-quality polymer fractions, which could at least to some extent substitute the virgin polymers in high-quality products. In addition, the pricing of the recycled polymers should be competitive. The specific requirements for enabling technologies vary remarkably depending

Method	Instance of use	Restrictions	Implementation requirements	TRL	Throughput rate, tonnes per hour (t/h)
NIR spectroscopy	polymer sorting	not suitable for black plastics	already available	9	whole containers: 0.5–10 t/h flakes: 0.2–9 t/h
UV–visible (VIS) spectroscopy	colour-based sorting	-	already available	9	whole containers: 0.8–10 t/h flakes: 0.6–6 t/h
CCD camera	colour-based and shape-based sorting	-	already available	9	whole containers: 0.5–9 t/h flakes: 0.2–9 t/h
XRF spectroscopy	screening of heavy elements	requires shielding	already available	9	flakes: for glass, 28 t/h
NIR-HSI spectroscopy	polymer sorting	not suitable for black plastics	already available	8	whole containers: 15 t/h, 10 t/h
MIR spectroscopy	polymer sorting, including black plastics	-	-	7	**purely MIR-based sorter data not available**
Mid-infrared hyperspectral imagery (MIR-HSI)	polymer sorting, including black plastics	-	-	7	**for sorter units, data unavailable** flakes (2 x 2 cm): 18 t/h
MDS	polymer sorting based on density	requires shredding plastics	requires flotation and magnetic particles	6	1.5 t/h
tracer	polymer sorting, BRF vs. no BFR, food grade vs. non-food grade	requires packaging redesign	requires a VIS or CCD camera	6	N/A; same as VIS or CCD camera
Raman hyperspectral imaging	polymer sorting	accurate focusing needed	-	6	whole containers: 0.1–0.4 t/h flakes (**conventional Raman Raman hyperspectral imaging-based sorters not available):** 2.4–3 t/h (Powersort 200), up to 10 t/h (Powersort 360)
LIBS	polymer sorting, screening of heavy and light elements	accurate focusing needed; currently point measurement only	-	4	**data for plastics unavailable** for metals: 5 t/h, several t/h
water-marking	polymer sorting, BRF vs. no BFR, food grade vs. non-food grade	requires packaging redesign	requires CCD camera	**unknown;** estimation: 4	N/A; same as CCD camera

Table 2. Estimated technology readiness levels of each solution in waste sorting units. Instances of use, restrictions, implementation requirements and throughput rates are also listed. The technology readiness level (TRL) scale is based on EU standards, with a range from 0 to 9. See the public report for more details.

on the local regulations, collection scheme and incentives adopted, MRF type and capacity, potential usage of recycled polymers, etc. The material classification solutions should be able to identify current mainstream polymers, novel bio-based plastics and additives in the polymers. The sorting technologies should be easily configurable to meet the changing requirements, for example in terms of polymer types, colours and product types. The traceability of the material flows should be improved in order to transform the collection and sorting ecosystem into a data-driven process, where the material flows can be predicted and optimised.

Results

A project report was written to examine the following:

- different alternatives to NIR spectroscopy that can be used to overcome its limitations
- previous research on factors affecting sorting accuracy
- current and future difficulties as well as requirements for sorting were listed (e.g. distinguishing food-grade from non-food-grade packaging plastic), and potential technologies as solutions

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BENEFITS FOR PARTICIPANTS

KUUSAKOSKI

We at Kuusakoski restore value to waste material by collecting, processing, and upgrading it into a new raw material. With a history that spans over 100 years, we are a reliable partner and a pioneer in the circular economy, committed to providing service in accordance with the values of a stable family business. Striving to gain a deeper understanding of materials and recycling drives our innovations, and helps us create increasingly efficient recycling solutions.

"We focused on developing the recycling of difficult plastics from waste electrical and electronic equipment (WEEE) and end-of-life Vehicles (ELV). The goal was to promote the recycling and recycling business of plastics for more efficient material recovery, more valuable recycled raw materials, and a renewed, flexible, and customer-oriented production model and new partners. The PLASTin consortium proved to be an excellent expert network. The research carried out in all parts of the PLASTin project clearly contributed to meeting our goals. We gained a good deal of important knowledge and know-how for promoting the sustainable recycling of plastics. We particularly value the knowledge gained on maintaining and improving the quality of recycled plastics and the management of contaminants."

Kuusakoski Oy, **Tiina Malin**, R&D Manager

INDUSTRIAL ACCEPTANCE OF RECYCLED PLASTICS IN PACKAGING

	Difficulties	Obstacles	Opportunities
Product requirements for recycled plastic packaging	- Excessively strict requirements for some applications - Standardization and verification	- Legislation - Foodstuff contact - Product safety	- Use of monomaterials - Chemical recycling - Improved image
Supplementary or changed properties of recycled plastic packaging	– Degraded packaging functions - Increased food losses - Increased risk	- Satisfactory performance and properties - Limited availability of recycled plastics	- Use of monomaterials - New applications - Mechanical recycling

Table 3. Factors influencing industrial adoption of recycled plastics in packaging

Description

The recovery and recycling of plastics in packaging need to be developed to meet the demands from increased environmental awareness and more stringent regulation. The properties of recycled plastics should correspond to the requirements for their end use. New and improved technical solutions to the mechanical and chemical recycling of plastic can be used to increase the recycling rate of plastic waste.

A qualitative study was conducted to investigate the adoption, opportunities and difficulties related to recycled plastics in packaging. Project partners, producers and end users of packaging materials were interviewed as part of the qualitative research, and the industrial fields of the interviewees were categorised into the food sector and other sectors.

Properties of virgin and recycled plastic materials were compared experimentally to support the qualitative findings. Thermoformability and the tensile properties of VPET (Virgin Polyethylene terephthalate) and 50–80% mixed blend recycled polyethylene terephthalate (RPET) films were investigated at laboratory scale to outline how the mechanical properties and quality of recycled plastic packaging differ from those of virgin plastic packaging.

Results

The interviewees from the food sector showed an increased willingness to adopt recycled plastic packaging, yet the strict regulatory framework makes it difficult. Improved recycling of plastics in the food sector is primarily carried out using monomaterials, and the plastics in food packaging can be reduced by using thinner packaging.

The unavailability and impurity of the recycled plastics was recognised as a major obstacle to the adoption of recycled plastics in the packaging among the interviewees in the non-food sector. Moreover, laws and regulations limit the use of recycled plastics in the applications in which it might be otherwise possible. Recognised difficulties, obstacles, and opportunities related to the use of recycled plastics in packaging are summarised in Table 3.

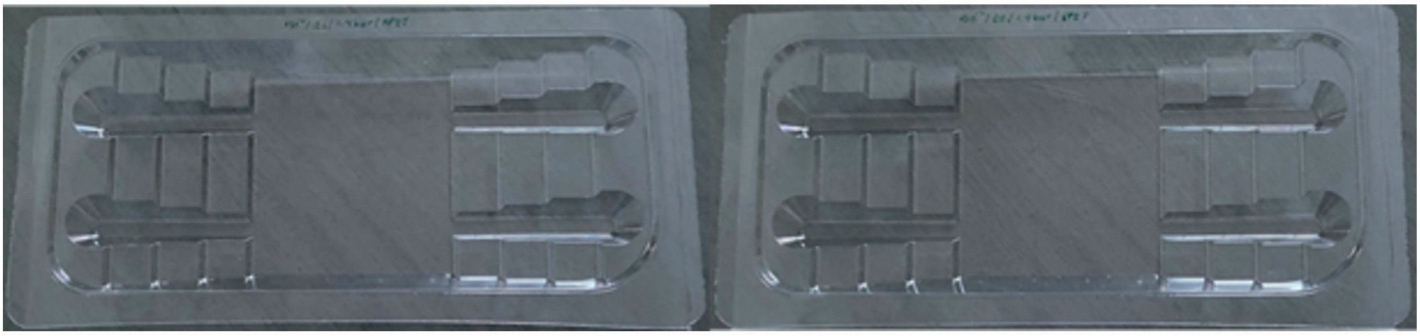

Figure 9. Thermoformed VPET (left) and RPET (right) tray packaging

In the food sector, the properties of recycled plastic packaging should fulfil requirements related to the durability, performance, and quality of packaging. The recycled plastics should align with the rules and regulations throughout their life cycle, both in the food sector and other sectors. The interviewees in the non-food sector indicated of possible compromises which can be allowed to the pricing, thickness, or colouring of the recycled plastic packaging if the performance and properties are satisfactory.

The experimental results showed almost no differences in the thermoformability and the tensile properties of virgin and recycled PET films. Visual quality of thermoformed virgin and recycled plastic packaging appeared identical, as seen in Figure 9. Based on the obtained qualitative and experimental results, recycled plastic packaging materials can meet the technical requirements for some industrial applications.

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Publications

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RESEARCH THEME 3

RECYCLING OF DIFFICULT PLASTIC FRACTIONS

Introduction

In order to reach the ambitious targets for the recycling rates set by the EU strategy, recycling must also be extended to plastic fractions that are difficult to process. Both WEEE and liquid board packaging already have a working infrastructure for collection, transport and recycling, but the recovered plastic is usually either incinerated, disposed of in landfills or transported to other EU countries. The recovered plastics are difficult to recycle, since they may contain harmful additives or they are fused to multimaterial structures that are difficult to separate. In order to use the plastics as raw material for new applications in the best possible manner, the existing identification, separation and processing procedures need to be improved. The new procedures have to be economical and more environmentally sustainable than the ones that are currently used.

1. Liquid Packaging Board

Summary, key results and impacts

Liquid packaging board (LPB) is one of the fastest-growing packaging materials. Even though LPB provides significant advantages, it has presented difficulties for the existing waste management sector since its introduction. The repulping process that is used to recycle the carboard and liquid packaging board packaging extracts cellulose fibres for reuse, but the plastics are left into a side stream – referred to as repulping reject – with aluminium and some types of residual fibres. Since LPB packaging has a plastic content of more than 5%, their proportion is considered when calculating the national recycling rates for plastics. Since the rejects are currently mostly incinerated, their recycling could help to achieve the future EU recycling targets.

The work on the third research theme focused on studying the technical and environmental aspects of using repulping reject. The research revealed that the repulping rejects contain 42 to 75 wt% of plastics. The exact composition depends on the national collection system and is highest when the LPB packaging are collected separately from the other carboard packaging. The plastics in the reject are the same grades that are typically used to make LPB packaging: Low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), polypropylene (PP), ethylene vinyl alcohol (EVOH) and polyethylene terephthalate (PET).

HDPE is used in the caps and necks of containers, and are relatively easy to separate from the reject. As such, they could be used to produce recycled HDPE.

Some of the plastics are fused with other plastics, residual fibres and aluminium, making their separation much more difficult. The state-of-the-art separation systems that enable enchanted removal of fibres and even extraction of aluminium from the rejects were surveyed in the research.

Direct compounding of the rejects to plastic-fibre-aluminium composite was studied as an alternative route for mechanical recycling as it does not require any separation. All the rejects studied were processable with common melt processing techniques such as extrusion, injection moulding and rotational moulding. Compared to the commercial wood plastic composites, the mechanical properties of the compounds were slightly lower in terms of stiffness and strength, but the properties could be modified by adjusting the composition. Increasing the mechanical recycling of LPB by reusing its fibrous and plastic fractions in the moulded pulp applications also presents an interesting approach for a more sustained recycling of multilayer packaging materials.

From an environmental point of view, the mechanical recycling of the reject could have the lowest global warming potential (GWP) if the recycled reject plastics could replace at least 30% of virgin plastics. In addition, chemical recycling can decrease the GWP of reject recovery by 70% compared to incineration.

BENEFITS FOR PARTICIPANTS

NESTE CORPORATION

Creating the foundations of the future circular plastics ecosystem with advanced recycling techniques

Neste creates chemical recycling solutions and is committed to speeding the transition to the circular economy. Neste's ambitious goal is to process more than 1 million tonnes of waste plastic annually from 2030.

To reach our goals and accelerate the circular economy for plastics, we want to collaborate, develop and implement the most sustainable solutions possible for recycling waste plastics.

Through the PLASTin project, Neste gained valuable insight into the potential of recovered waste plastic flows in the light of foreseeable changes in the operating environment.

Working with partners in industry and the research sector reinforced our vision that the optimal circular economy for plastics consists of parallel mechanical and chemical recycling solutions to maximise the recycling rate and material recovery and processing efficiency, and to minimise the use of waste incineration and landfills, both of which are environmentally harmful means of handling waste.

Although this collaborative project focused on Finland, we believe that most of the findings will be applicable to the broader European and global contexts as well.

Neste Corporation, **Jarmo Kela**, R&D Program Manager

COMPOSITION OF THE REPULPING REJECTS

	Composition (wt%)			
	Moisture	Cellulose	Polymers	Aluminium and others
LPB batch 1	0.0	8.8	73.5	15.7
LPB batch 2	0.0	8.0	75.0	13.0
Carboard and LPB supplier 1 batch 1	3.0	39.3	42.2	12.6
Carboard and LPB supplier 1 batch 2	1.0	18.0	66.0	11.0
Carboard and LPB supplier 2 batch 1	3.0	29.9	51.0	13.6
Carboard and LPB supplier 2 batch 2	3.6	28.0	54.1	10.6
LPB industry side stream	0.0	11.0	87.0	1.0

Table 4. Compositions of the different samples.

Description

The knowledge about the composition of the repulping rejects is important to evaluate the possibility of making use of its different fractions. In this study, the repulping reject is a side stream of the cardboard and liquid packaging board packaging recycling process that extracts cellulose fibres for reuse. The rejects contain moisture, residual fibres, plastic and aluminium, but the exact composition depends on the nature of the feedstock. To study the effect of the feedstock on the compositions several samples of repulping rejects were studied from different suppliers. The samples were recovered from the recycling of separately collected consumer packaging and from the industrial side stream of liquid packaging board manufacturing.

Results

The composition of the rejects was studied with thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). The study revealed that the composition of the rejects depends on several factors. The rejects from the consumer waste were more mixed compared to the reject from the industrial side stream, as expected. Consumer reject contains several different polymers (LDPE, LLDPE, HDPE, PP or EVOH and PET), cellulose, and aluminium, whereas the industrial reject contains only LDPE, PET and cellulose. The collection system of the municipal waste influences on the composition as well. In Finland, cardboard and liquid packaging board (LPB) are collected in the same bin, but in Germany and a number of other EU countries LPB

	Polymers in the samples			
	LDPE	LLD/HDPE	PP/EVOH	PET
LPB batch 1	X	X	X	X
LPB batch 2	X	X	X	X
Carboard and LPB supplier 1 batch 1	X	X	X	
Carboard and LPB supplier 1 batch 2	X	X	X	X
Carboard and LPB supplier 2 batch 1	X	X	X	
Carboard and LPB supplier 2 batch 2	X	X	X	X
LPB industry side stream	X			X

Table 5. Polymers in various samples.

packaging is collected separately. The rejects contain the same polymers, cellulose, and aluminium, but the ratio of polymers to residue fibres is higher in the LPB reject. The composition can also vary from batch to batch depending on the supplier and processing date. The fibre and polymer portions of the studied rejects from mixed cardboard and LPB packaging varied between 18 and 39 wt-% for cellulose, and between 42 and 66 wt-% in the case of polymer. The compositions of the different samples are listed in the Table 4 and polymers in the different samples in the Table 5.

The results show that the rejects have high polymer concentrations and are therefore a potential source of recycled polymers. The polymer grades correlate well with the polymers that are typically used to manufacture liquid carton packaging. Mechanical separation of all polymers from the rejects is difficult, as they contain aseptic packaging that typically have multi-layered coating structures where different plastics and/or aluminium are fused together. HDPE is relatively easy to separate, as it is mostly used to make the caps and necks of packaging. These are present in the reject as separate particles, and have thicker walls than is the case with film-like coatings. They could be separated from other materials using air flow-based cyclone separators. A manual separation test showed the HDPE fraction to be around 5 wt%.

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ADVANCED SEPARATION TECHNIQUES IN THE REPULPING OF LIQUID PACKAGING BOARD

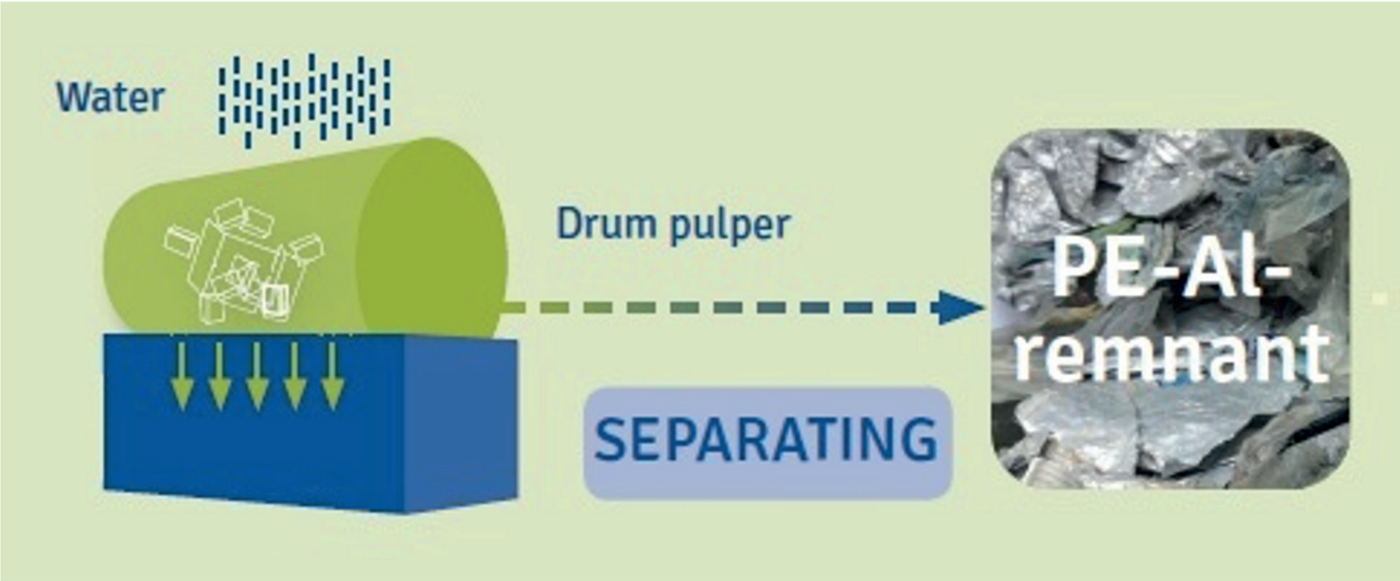


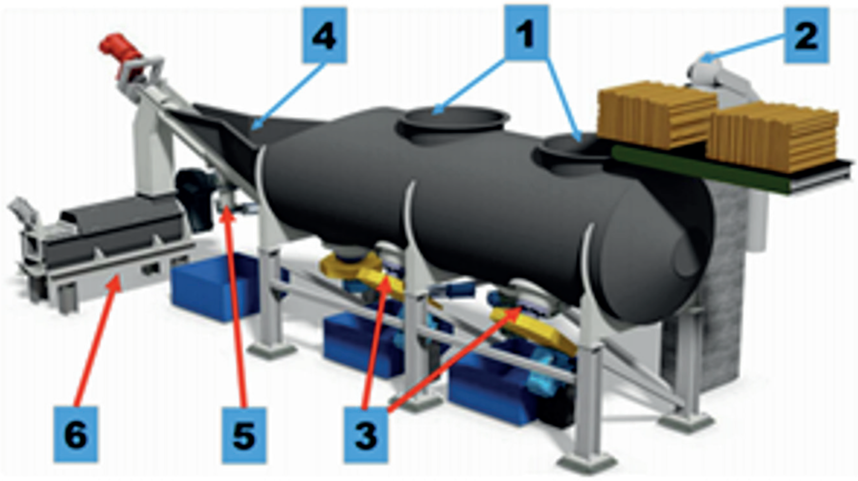
Figure 10. Repulping of liquid packaging board with a drum pulper, the repulping reject is extracted for further separation and processing of plastic fractions and aluminium (Mod. Palurec GmbH 2022)

Description

Conventional repulping of liquid packaging board yields repulping reject with fibres, plastic, and possibly aluminium. Repulping involves mechanical separation of the material layers. Water is added to dissolve the fibres, which are then passed through a repulper as the plastic and the aluminium fractions are collected. Consequently, the repulper operates using a method similar to a washing machine. A German-based Palurec GmbH operates a recycling plant for liquid packaging board, and the repulping process of Palurec utilises a drum pulper to separate the plastic and the aluminium fractions from the fibrous content of liquid packaging board. The rotating drum pulper is a good example of a repulping method that operates similarly to a washing machine. Palurec's drum pulper is presented in Figure 10.

State-of-the-art separation systems can be used to improve the repulping of liquid packaging board by providing fibre-free reject. The fibre-free reject consequently enables a more economical processing and reuse of plastic and aluminium fractions of liquid board packaging. Disintegration of liquid packaging board during the separation of its material components as part of the repulping is demanding due to its high wet strength. A number of different state-of-the-art separation systems were investigated to study industrial solutions to the repulping of liquid packaging board. As part of the benchmarking, repulping reject of liquid packaging board from industrial waste streams was requested and thereafter obtained for the experimental part of the third research theme, related to the processing of repulping rejects.

Figure 11. SimplyOne pulper with (1) pulping unit, (2) ragger, (3) coarse screener, (4) reject washer, (5) heavy reject remover, and (6) reject compactor (PR Pulping Oy 2021)



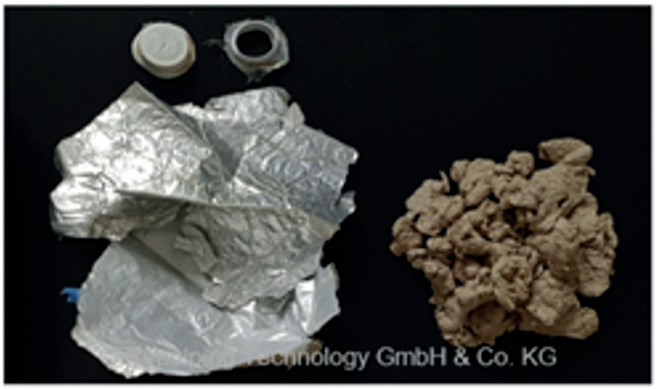


Figure 12. Input (left) and output (right) of a repulper after separation of liquid board packaging with a cavitation pulper (Mod. Repulping Technology GmbH 2021)

Results

State-of-the-art separation systems enhance the separation of LPB material layers by prolonging the disintegration time of the repulping. The prolonged disintegration time can be enabled by combining all repulping stages into one equipment which then reduces the delay between the repulping stages, and compensates for the delays with a longer disintegration time. Example of a simplified pulper with integrated repulping stages is shown in Figure 11.

Alternatively, the increase of shearing forces during the separation of liquid board packaging can be used to recover repulping reject with minimised fibrous content. The shearing of material layers during the separation can be increased with the use of cavitation. A repulping unit with an underpressurised vessel containing water, shearing blades, and liquid board packaging will accelerate the separation of the material layers due to wear caused by bursting air bubbles near the shearing blades and the wet disintegrating liquid board packaging. Enhanced separation of material layers during repulping of LPB with a cavitation pulper is shown in Figure 12.

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BENEFITS FOR PARTICIPANTS

BOREALIS POLYMERS

Borealis

Borealis is one of the world's leading providers of advanced and circular polyolefin solutions and a European market leader in base chemicals, fertilizers and the mechanical recycling of plastics. We use our expertise in polymers and decades of experience to offer valuable, innovative and circular material solutions for key industries. In re-inventing for more sustainable living, we build on our commitment to safety and our expertise as we expand geographically and accelerate the transformation to the circular economy.

Borealis in Porvoo, Finland

Borealis' production facility in Porvoo, southern Finland is a fully integrated petrochemical complex consisting of an innovation centre and six production plants: a cracker for the production of olefins (ethylene, propylene and butadiene), a phenol and aromatics plant, two plants for polyethylene PE (one of which is a Borstar plant), a polypropylene (PP) unit, and a compounding unit. The main products are pipe, packaging and cable products. Borealis' innovation centre in Porvoo focuses on catalyst and process research and includes catalyst scale-up facilities and fully integrated Borstar PE and PP semi-commercial pilot plant lines. Borealis has around 900 employees in Finland.

Our long-term strategic aim is sustainable plastics industry transformation (SPIRIT) in Finland. Research and development carried out in the PLASTin project is especially helpful from the point of view of shaping the market. Developing plastics circularity is quite a local activity, and thus it is important for us to collaborate in the Finnish plastics value chain as well as cooperating with the Finnish authorities.

Borealis, **Auli Nummila-Pakarinen,** Application Technology Manager

BENEFITS FOR PARTICIPANTS

ROSK'N ROLL

Plastics in municipal waste management systems

Rosk'n Roll is a municipal waste management company owned by twelve municipalities in eastern and western Uusimaa area. There are approximately 250,000 residents in the area we operate in. We provide a range of possibilities for sorting waste plastics. For example, customers can choose to use multi-compartment waste bins, which also have a compartment for plastic packaging. In addition, for over two years we have been collecting waste plastic products in our 15 waste stations.

Participating in the PLASTin project allowed up to gain a good understanding of the development of plastic waste material flows and different sorting methods of plastics, and also to gain further insight into the difficulties in the recycling system. This information is very useful in developing our own pre-sorting, collection and treatment system with our partner companies. The results of this project will also help us in dialogue and communication with residents. We are asked many questions in our everyday interactions with residents, such as why all plastics cannot be put together in the same waste collection, or why people are not paid for sorting recyclable materials. The PLASTinn project has also allowed us to gain a better understanding of possible solutions and future visions concerning plastics and plastics recycling in general.

Rosk'n Roll Oy Ab, **Vesa Heikkonen**, CEO

PROCESSING OF THE REJECTS

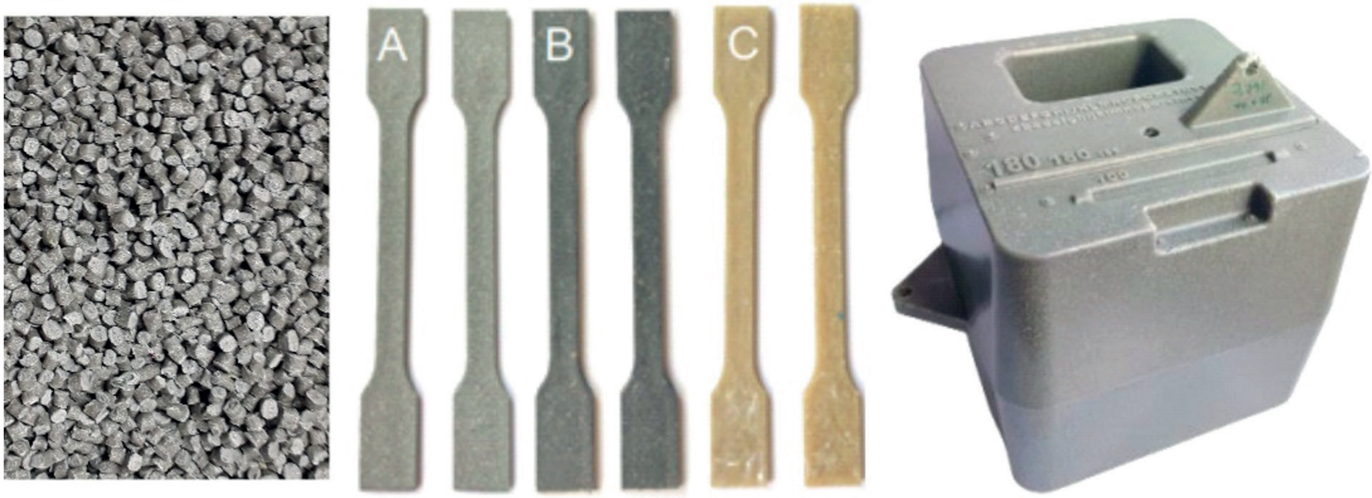

Figure 13. Extruded granulates, injection-moulded tensile test specimen and rotational moulded sample

Description

Three of the studied rejects were selected for the processing trials. The processing of the unseparated rejects was carried out in several steps where the fluffy reject was first pressed into thicker sheets with a heated press that where then ground into flakes finally compounded with a twin-screw extruder to produce granulates. The granulates were injection-moulded to form a specimen for tensile-testing. The granulates from the LPB reject were also ground to powder that was mixed with virgin LLDPE powder and processed with rotational moulding. Processing was possible with 30/70 (wt/wt) and 70/30 reject/virgin LLDPE fractions, but the quality was better with the smaller reject concentration. Overall, the processing of the rejects was possible with normal melt processing techniques.

Results

Tensile-testing specimens from different rejects were tested for tensile strength and the results were analysed. Table 6 tabulates the tensile modulus, tensile strength and elongation at break determined from the stress-strain curves. The composition had a notable effect on the tensile properties. The cellulose fibres act as reinforcing fibres in the polymers, increasing the tensile modulus and tensile strength while also reducing the elongation at break. The HDPE seems to increase the modulus and reduce the elongation at break as well based on the differences between LBP and Industry side stream samples. Unmolten PET flakes, especially in the LPB reject, also seem to reduce the ductility. If the properties are compared to the commercial wood plastic composites tabulated in Table 7, it is obvious that

Sample	Cellulose concentration (%)	Tensile modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
LPB batch 2	8	883	13.6	8.9
Carboard and LPB supplier 1 batch 2	18	1219	11.4	4.6
Industry side stream	11	514	14.9	22.8
LBP after fibre extraction	2	726	13.1	9.2
Carboard and LPB after fibre extraction	4	797	11.5	5.3

Table 6. Tensile modulus, tensile strength and elongation at break for selected samples

Material	Manufacturer	Composition	Cellulose concentration (%)	Tensile modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
Durasense Recycled	Stora Enso	wood fibre and recycled polymers	30–50	3200–5000	30–45	2.5-5
UPM Formi EXP	UPM	cellulose fibre and virgin PP	20	1800	33	10
UPM Formi HP	UPM	cellulose fibre and virgin PP	20	2100	37	6.7

Table 7. Properties of commercial wood plastic composites.

commercial materials have a higher tensile modulus and tensile strength. However, they typically also have a higher cellulose concentration that could explain part of the difference. Modification of the cellulose content could therefore be a way to adapt the properties of the compounds for different applications. To verify this assumption, the previously studied samples were repulped to extract as much fibre as possible before granulation. The extraction was successful, and the cellulose concentration was reduced significantly. The effect was seen in the mechanical properties mostly as decrease in the tensile modulus as expected.

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Publications

Mäki-Tulokas, S. 2021. Recycling of plastics from liquid carton packaging. Master's thesis. https://urn.fi/URN:NBN:fi:tuni-202111188532

PRESS-FORMING MOULDED PULP FROM REPULPING FRACTIONS OF LIQUID PACKAGING BOARD

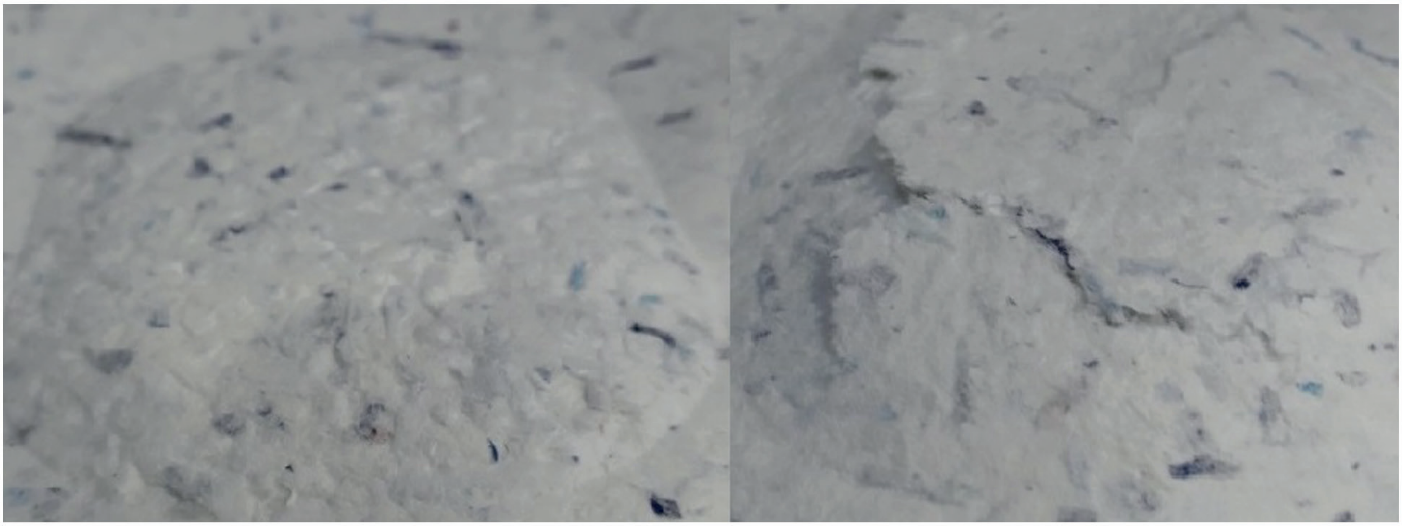

Figure 14. A successful (left) and a damaged (right) moulded pulp sample

Description

Plastic fraction of repulped liquid packaging board ends up in the repulping reject, and thereafter the reject is commonly incinerated. As discussed before, the reject contains plastic, aluminium, and some fibres. The fibres in the reject prevent reuse of the plastic or the aluminium fraction as fully recyclable raw materials. The fibrous content in the reject can be reduced with a more effective separation of the material layers from the reject, yet the bulk of the fibrous fraction is already recovered using conventional repulping techniques.

The recycling of LPB without the separation of the material layers by the repulping as been tested by Hwang et al. (2006) to study the reuse of LPB in composite board applications. The reuse of unseparated LPB material fractions can be considered an alternative upcycling route for the plastic and the fibrous fraction of LPB. Moulded pulp materials of electronic equipment packaging can be developed from a pulp-plastic composite (Noguchi et al. 1998), and the unseparated LPB material fractions similarly offer a suitable raw material source for moulded pulp packaging.

A proof of concept for using repulping fractions of LPB as a moulded pulp material was outlined. Laboratory sheets were manufactured from the repulp of separately collected LPB containing 75% fibres and 25% plastics. A convertibility evaluation was conducted for the laboratory sheets using a press-forming toolset. Heat input and pressing force were altered in the press-forming experiments to compare their effects to the maximum forming depth of the moulded pulp samples. Tensile tests were conducted with the laboratory sheets, and defect formation from the press-forming of the moulded pulp samples was observed visually. A comparison of a successful and a damaged sample is visualised in Figure 14.

Results

Repulping fractions of LPB were successfully used as a raw material in the press-formed moulded pulp samples. However, the maximum forming depth of the moulded pulp samples was limited. The results showed a positive effect from the increased heat input to the maximum forming depth, and the finding was in good agreement with the previous research (Vishtal et al. 2013).

Press-forming proved feasible in the manufacturing of moulded pulp provided that the dewatering of the material is ensured. Suitable dewatering methods for the laboratory sheets include wet pressing and drum drying. In dewatering the material, the appropriate moisture content for press-forming it must be ensured. The defect formation in the press-formed moulded pulp samples occurred in the flange and bottom regions of the samples. The defect formation was linked to the reduced material thickness in the flange and bottom regions due to compression of the material from the material-tool contact.

Only a minor tensile strength and strain at break was achieved with the tested material. The limited tensile properties and maximum forming depth was associated with a fragile structure of the laboratory sheets. The fragile structure was found to be due to the disruptive effect of the plastics on the fibre network and the bonding of the fibres. The use of fillers and compatibilizers as part of the manufacturing of the laboratory sheets from the repulp of LPB was suggested for future research to improve the convertibility and the mechanical properties of the moulded pulp material.

Increasing the mechanical recycling of LPB by reusing its fibrous and plastic fractions in the moulded pulp applications presents an interesting approach for a more sustained recycling of multilayer packaging materials.

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CARBON FOOTPRINT OF DIFFERENT RECOVERY OPTIONS FOR THE REPULPING REJECT FROM LIQUID PACKAGING BOARD TREATMENT: LIFE CYCLE ASSESSMENT

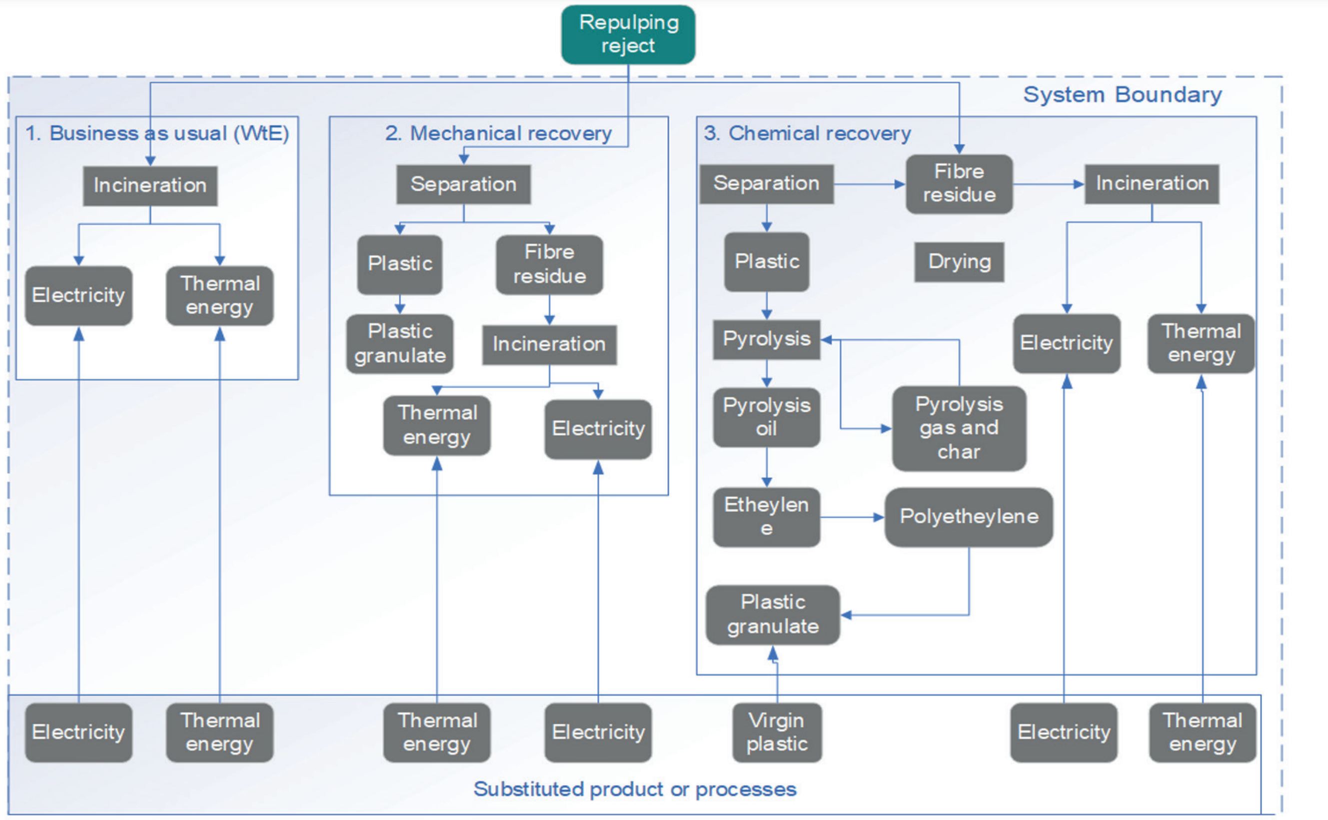

Figure 15. System boundary

Description

In most European countries, LPB waste is either incinerated or recycled in the recycling facilities where fibre is recycled, and the repulping reject is separated for incineration. Mechanical recycling and chemical recycling processes are other options for repulping reject treatment. In this study, a life cycle assessment was conducted to compare the environmental impacts of three treatment processes, incineration (scenario 1), mechanical recycling (scenario 2) and chemical recycling (scenario 3); each was considered with the functional unit of 1 tonne of repulping reject. Furthermore, each of the scenarios was divided into two sub-scenarios (1.1,1.2; 2.1,2.2; 3.1,3.2) based on the substituted heat produced from the treatment processes.

This study used the 0:100 end-of-life (EoL) method with a credit system. Credit was gained by avoiding the environmental impact when the recovered energy and material replaced the virgin materials and energy from the production mix. Electricity is recovered in each scenario, and replaces the electricity production of Finland in 2017 (peat 4.13%, hard coal 8.73%, coal gases 0.87%, natural gas 4.92%, fuel oil 0.27%, biomass 16.22%, biogas 0.62%, waste 1.53%, nuclear power 33.49%, hydroelectric power 22.01%, wind power 7.14%, photovoltaic power

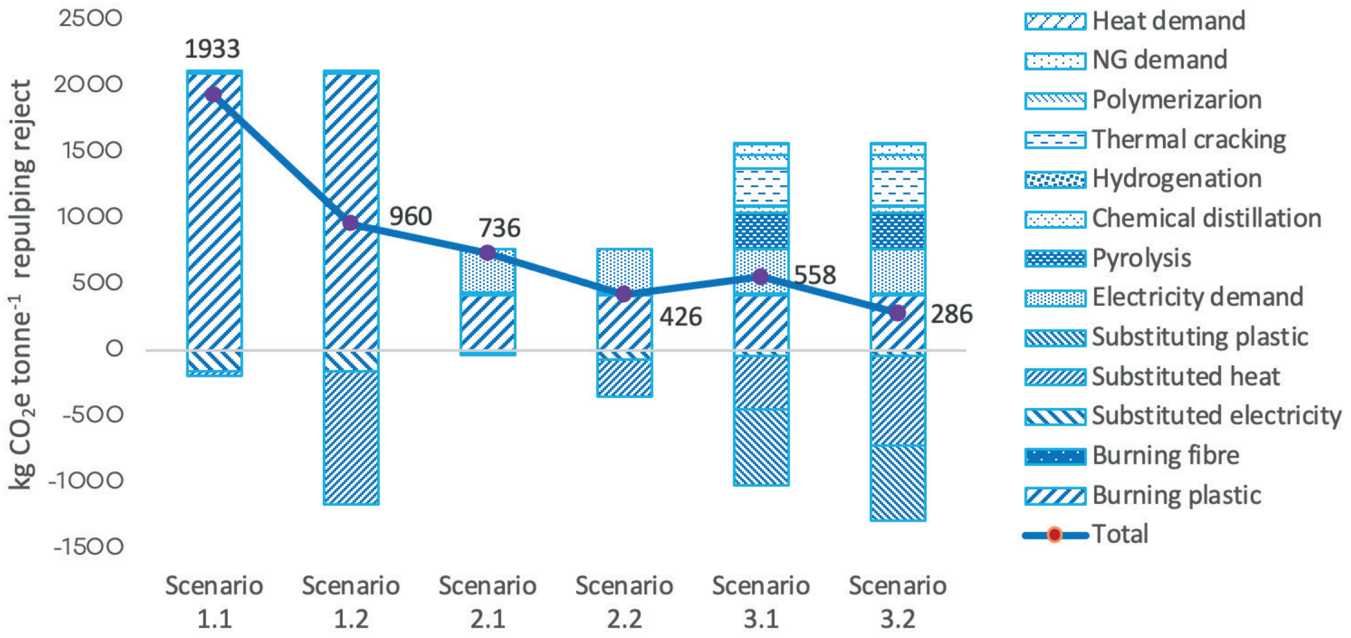

Figure 16. Results of the carbon footprint analysis of LPB waste recovery options.

0.07%). Thermal energy is also recovered, and substitutes thermal energy produced from biomass (sub-scenario X.1) or natural gas (sub-scenario X.2). In addition to electricity and heat, the chemical recycling routes also recycle plastic, which replaces virgin polyethene (PE).

Results

The results of the three reject treatment scenarios illustrated in Figure 16 depend on several factors, such as the substitution of biomass-based heat source and natural gas-based heat source, avoided emission by substituting energy and virgin plastic, and energy consumption in recycling. It was found that waste incineration scenarios (1.1 and 1.2) had the maximum climate change impact compared to mechanical recycling and chemical recycling scenarios. In contrast, chemical recycling scenarios had the lowest climate change impact than mechanical recycling scenarios and waste incineration scenarios. The chemical recycling scenarios replaced 300 kg of virgin plastic. By contrast, the mechanical recycling process did not replace virgin plastic. Consequently, scenarios 3.1 and 3.2 had a better climate change impact than scenarios 2.1 and 2.2.

The uncertainty analysis of the study (Figure 16) shows that the impact of the virgin replacement ratio had a significant impact on the overall result of the study. An increase in the replacement ratio by mechanical recycling resulted in a decrease in the total emissions due to the increase in the avoided emission by replacing virgin plastic. Mechanical recycling had a lower climate change impact than chemical recycling only when it replaced 30%, 50%, 80%, and 100% virgin plastic. However, replacing virgin plastic with the mechanical recycling process is a highly optimistic proposition which it difficult to fulfil with current separation technologies.

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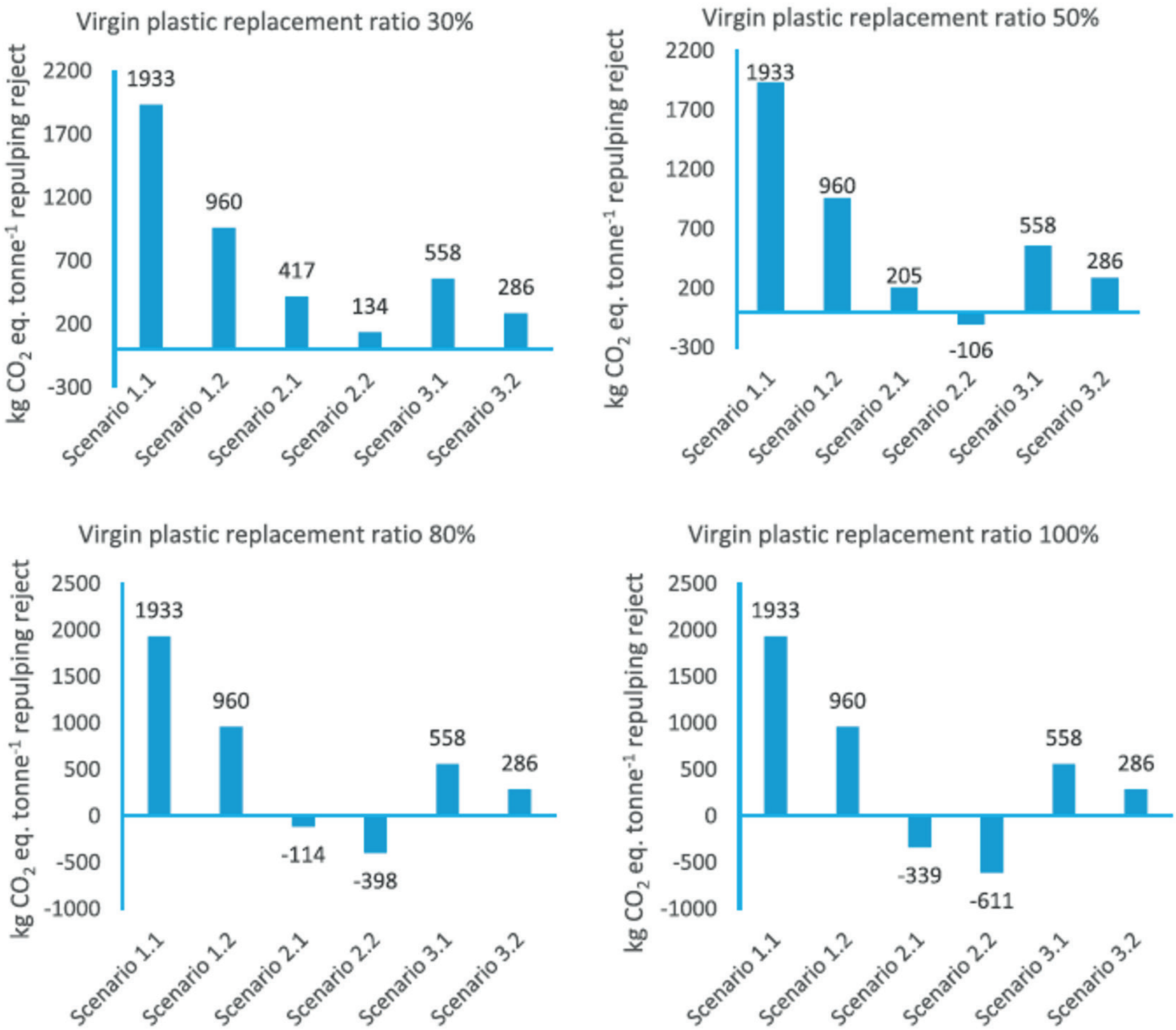

Figure 17. Results of the uncertainty analysis of LPB waste recovery options based on virgin plastic replacement ratio.

RECYCLING OF DIFFICULT PLASTIC FRACTIONS

2. Waste Electrical and Electronic Equipment

Summary, key results and impacts

Technological development is needed to manage chemicals in the circular economy. Innovations are needed, such as new methods for identifying substances in waste streams. For example, recycling of waste electrical and electronic equipment (WEEE) plastics is difficult due to the various additives and possible high concentrations of hazardous substances used in electrical and electronic equipment (EEE) plastics. Chemical legislation protects human health and environment from the risks posed by chemicals. Restrictions on hazardous substances also helps promote safety in the circular economy. Managing chemicals in recycling requires continued research to avoid harmful chemicals ending up into new products.

Laser-based spectroscopic methods were studied for characterising plastics from the WEEE stream in terms of their brominated flame retardant (BFR) composition. XRF spectroscopy, which is commonly used, was used as a benchmark for testing Raman, and active hyperspectral imaging (AHS) and LIBS were used for quantifying the elemental bromine concentration of over 200 plastic samples. In addition, laboratory-made samples containing known BFRs and a small set (25) of chemically analysed WEEE plastic samples were used to test whether Raman and laser-induced breakdown spectroscopy (LIBS) could be used to identify the exact BFR. According to the results, Raman and AHS can be used to identify high-bromine samples from low-bromine ones, although with a relatively high threshold, whereas LIBS is very accurate in quantifying the concentration. Moreover, Raman and combination of Raman and LIBS show promise in classifying different BFRs inside plastics.

During the research, a test run was carried out for mixed WEEE plastics with an XRF-based separation line that separates brominated plastics from other types. The test run was successful, as the EDS analysis of the separated bromine-free plastic fraction did not reveal any traces of bromine, even though the line was running at low speed. The bromine-free plastics were further separated to different grades, injection-moulded and tensile-tested. The results were encouraging, as the mechanical properties compared well with virgin plastics. This indicates that they are suitable for use in many applications. However, the thermal stability was reduced, and antioxidants should therefore be added to the recycled plastics during compounding. Mechanical properties may also be improved with antioxidants and chain extenders.

The environmental impacts of WEEE recycling after separation of brominated plastics were compared to the cur-

rent energy recovery using a life cycle assessment. Mechanical recycling has the lowest GWP if the recycled plastics can adequately substitute virgin plastics. However, there is uncertainty in the substitution rate. Chemical recycling can also decrease the GWP impact by about 40% compared to incineration, although the yield of plastic products with pyrolysis seems rather low.

Acrylonitrile–butadiene–styrene (ABS) reject from WEEE was tested on a larger scale in a mechanical recycling line (VAREX). This method has been improved to retain the value of recycled plastic, and the idea is based on inline viscosity measurements and control of the recycled materials. This makes it possible to maintain or even upgrade the material properties by the addition of specific polymers or additives to enhance the quality of recycled thermoplastics. This trial showed that it is possible to adjust the viscosity by additivation using a VAREX controller. A correlation was also found between the impact strength and melt viscosity.

BENEFITS FOR PARTICIPANTS

GRIFFIN REFINERIES

Griffin creates value from waste through innovative waste management solutions

Griffin Refineries is a Finnish circular economy company that creates value from waste using innovative waste management solutions. By treating organic waste, recycling plastic, and transforming waste into more environmentally friendly fuel, Griffin helps companies regard waste as a useful and valuable resource based on circular economy principles, resulting in financial benefits and environmentally responsible actions.

Innovation being at its core, Griffin always aims for the best and viable combination of products and services for the benefit of the customers wherever they are situated. Griffin has entities in Dubai, London and Helsinki, and therefore has extensive knowledge of the local legislation and market circumstances in a wide range of countries.

Griffin contributed its waste management experience and insight on international waste markets, especially in the United Arab Emirates. Its reference project in the United Arab Emirates gave Griffin access to customer case data.

Through the PLASTin project, Griffin had access to the latest research information, and the workshops and research give the opportunity to learn more about plastics recycling concepts and technical solutions for the recycling of plastics. This knowledge is valuable when developing future commercial solutions for plastics recycling difficulties. Dialogue with other circular economy experts and recycling experts in both research and commercial organisations is essential for the continued development of plastic recycling.

Griffin Refineries Oy, **Anne Fraser-Vatto**, CFO, Business Unit Director

THE HARMFUL ADDITIVES IN WEEE PLASTICS AND THE REGULATORY FRAMEWORK

Description

In the circular economy, increasing the use of recycled plastics reduces the use of fossil based virgin materials. European Union has set recycling targets for waste electrical and electronic equipment (WEEE) in Annex V to the WEEE directive (2012/19/EU). It has been estimated that about 20% of the total weight of electrical and electronic equipment (EEE) may be plastics (Cesaro et al. 2017), and for this reason WEEE offers great potential as a source for recovery of plastics. However, arranging recycling for WEEE plastics is difficult on account of the possible high concentrations of hazardous substances used in EEE plastics.

Most concerns relate to the presence of halogenated flame retardants, and especially those containing brominate (BFRs) that are classified as persistent organic pollutants (POPs). Plastics may also contain various other additives or impurities, such as heavy metals, other POPs, and substances of very high concern (SVHCs). Moreover, chemicals used to substitute chemical that have already been restricted or are being phased out may be equally hazardous.

Results

Legislative framework

Extended producer responsibility (EPR) legislation requires that the producers of EEE are responsible of the whole life cycle of a product sold in the EU, including waste collection and recycling. Besides laying down rules for the EPR scheme for WEEE, the WEEE directive lists substances, mixtures and components that must be removed from WEEE prior to their recycling.

EU legislation on chemicals and products sets restrictions on the use of substances of concern that may limit the use of recycled materials in products. REACH Regulation ((EU) No. 1907/2006) lays down provisions on the registration, evaluation, authorisation, and restriction of chemical substances as such, in mixtures and in articles. Among other things, it sets restrictions on the use of chemicals in specified products and stipulates if the use of a specific substance requires authorisation from the European Commission. The EU regulation on persistent organic pollutants (Regulation (EU) 2019/1021) prohibits or restricts the use of persistent organic pollutants (POPs), with the exception of their presence as unintentional trace contaminants. In effect, the regulation prohibits the introduction of new POPs to the market and the recovery and disposal of waste in a manner that can lead to reintroducing the POPs into material streams. It also sets limit values for POPs in wastes. Wastes containing POP substances above those limits may not be recycled.

Besides EU chemicals legislation, product legislation can also affect the possible uses of recycled WEEE plastics by introducing product group specific requirements in addition to those contained in the general chemicals legislation.

Under the amendment (2018/851/EU) of the EU Waste Framework Directive (2008/98/EU), a database was established to facilitate tracking of the use of SVHCs and ensure that information is also available on the waste phase of a product. This database of information on substances of concern in articles is entitled 'Substances of Concern In articles, as such or in complex objects (Products)' (SCIP), and is maintained by the European Chemicals Agency (ECHA).

Emerging chemicals

There are various chemical additives that have been considered as suitable alternatives for already restricted or phased out harmful chemicals in WEEE plastics. These are called emerging chemicals, even though some of them have already been in use for several years or even decades. These identified suitable alternatives belong to a larger groups of chemicals, such as other brominated flame retardants and flame retardants containing chlorine or phosphorus. The latter group is further divided into non-halogenated phosphorus flame retardants and halogenated phosphorus flame retardants.

Concluding remarks

Chemical management in recycling needs continuous work in understanding what chemical substances we might be recycling unintentionally into new products. Avoiding the recycling of restricted chemicals demands continuous development of methods suitable for identifying substances, and separation techniques for different matrices and waste streams. Legislation is also becoming increasingly strict regarding the use of some substances that are already restricted or are being phased out from recycling processes. In addition, new methods for identifying substances from WEEE plastics are needed because the research on chemicals and increasing knowledge on the impacts of a given chemical on health and the environment may lead to restrictions on the use of new substances.

Chemicals should also be taken into account when products are designed, and the 'safe and sustainable by design' concept should be implemented (Patinha Caldeira et al. 2022). The recycling operators should continuously follow the development of chemical legislation and research on chemicals. New knowledge and databases such as the aforementioned SCIP database may help in keeping track of the use of harmful chemicals, such as SVHCs, and in their management in recycling WEEE plastics. Managing chemicals in recycling processes promotes a safe and sustainable circular economy.

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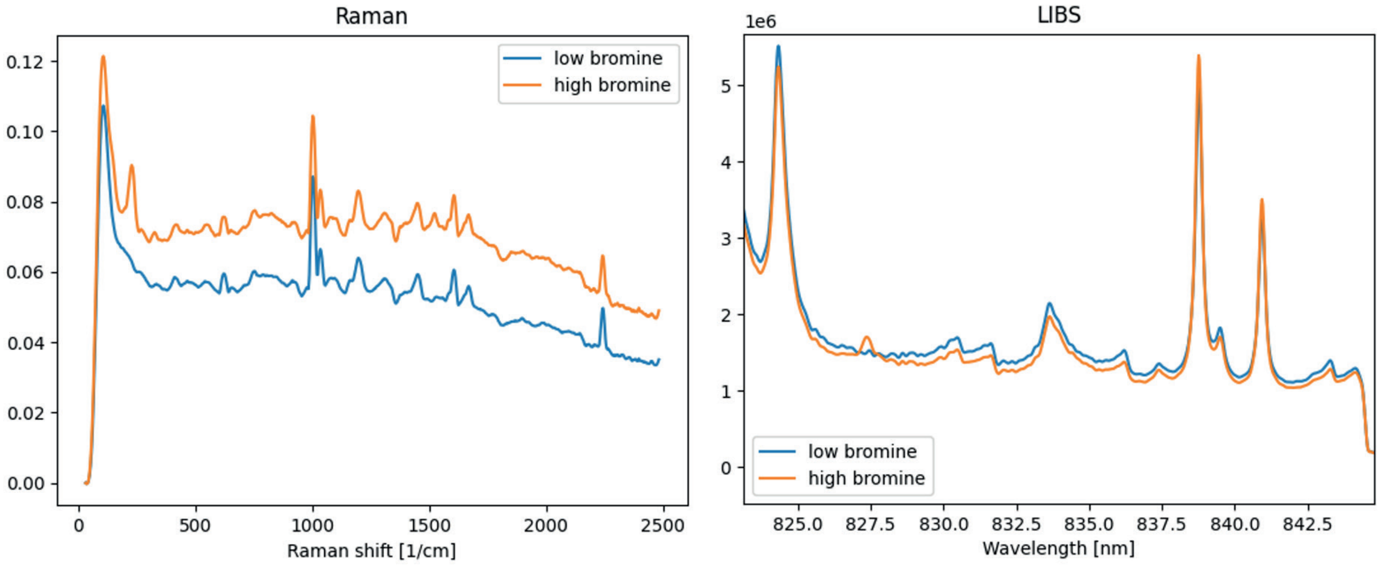

Figure 18. Raman hyperspectral imaging (left) and LIBS (right) spectra of the two ABS samples, one with a high concentration of BFR deca-BDE (16 wt%) and one with no additives. The distinguishing features of deca-BDE in the case of Raman spectroscopy occurs at 1523 cm-1. For LIBS, the peak at 827.4 nm corresponds to the atomic emission of elemental bromine.

Description

In Europe, over 2 million tonnes of plastic is produced from waste electronic and electric equipment (WEEE). Reprocessing this stream is hindered by impurities and even dangers to health and the environment, as in the case of brominated flame retardants (BFRs). In order to solve the problems related to recycling WEEE plastics, items containing these harmful additives should be sorted into their own fraction.

Experimental research strategy for WEEE plastic samples in this project: With current technology, it is possible to use XRF spectrometry on an industrial sorting line for separating the plastic fraction with a bromine concentration below the acceptable limit to be recycled as material. XRF spectroscopy was used to harvest WEEE samples that were then divided into two categories for experimental research by VTT, Tampere University and Arcada. The plastic samples below the acceptable bromine concentration were analysed to detect the presence of other harmful substances by laboratory methods at SYKE (phthalates and heavy metals were analysed quantitatively from selected samples), that might prevent their recycling as material, even if the bromine content were acceptable. The plastic samples above the acceptable bromine concentration limit were considered excellent material for research at VTT to experiment with novel spectroscopic analysis methods to distinguish BFRs in the polymer matrix. The work at VTT was supported by quantitative laboratory analyses of the selected BFR compounds of interest (analysis methods and services by THL).

Results of detection and identification studies

In this project, different spectroscopic methods were tested to see whether they could be used to distinguish BFRs in the polymer matrix. Calibrated lab samples were produced, and actual samples from the WEEE stream were acquired. These samples were analysed using XRF spectroscopy to measure their elemental bromine concentration. Following this, spectrum samples were taken using Raman spectroscopy and active hyperspectral imaging (AHS, a device developed by VTT). A small subset of the samples were also analysed using laser-induced breakdown spectroscopy (LIBS) and gas chromatography – mass spectrometry (GC-MS).

Applying machine learning to the combined Raman hyperspectral imaging and AHS spectra, the samples could be quite accurately classified to samples of either high (above 70,000 ppm) or low (below 70,000 ppm) elemental bromine concentration. Although a smaller sample set was used, preliminary results indicate that the LIBS spectrum can be used to quite accurately predict the elemental bromine concentration in the case of lab samples, and Raman hyperspectral imaging the combination of this imaging method with LIBS show promise in classifying different BFRs in plastics.

Results describing available chemical analysis methods and the observed needs for improvement to benefit the increasing material recycling of WEEE plastics

List of methods for detection, identification and quantification have been also previously studied, reported and used to analyse harmful substances (such as bromine, pthtalates, heavy metals). Existing methods rarely can be applied directly for chemically unfamiliar plastic samples, if they are developed and optimised for some other matrix (for example metals, water, soil, organic solutions, liquids). Many quantitative analysis methods for harmful substances in WEEE include extensive pretreatment for organic solid material samples before the quantitative chemical analysis is performed, for example with calibrated instrumental spectrometry. Plastics, including those used in WEEE applications, are highly varied in their chemical natures (and sometimes also physically). Because of this, the specific plastic matrix in question has an effect on the success of the pretreatment steps. Harmful substances are typically present in plastic matrix in small quantities, as additives for flame retardancy or for some other desired function. Chemical signals from additives easily disappear to organic mass of matrix polymer, which makes the direct detection and quantification without any pretreatment steps difficult or impossible. Verification that the chemical nature is suitable for WEEE plastics recycling includes sophisticated instrumental analytics and proven methods, and also requires plastics knowhow for troubleshooting.

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CHARACTERISATION OF RECYCLED WEEE PLASTIC PROPERTIES

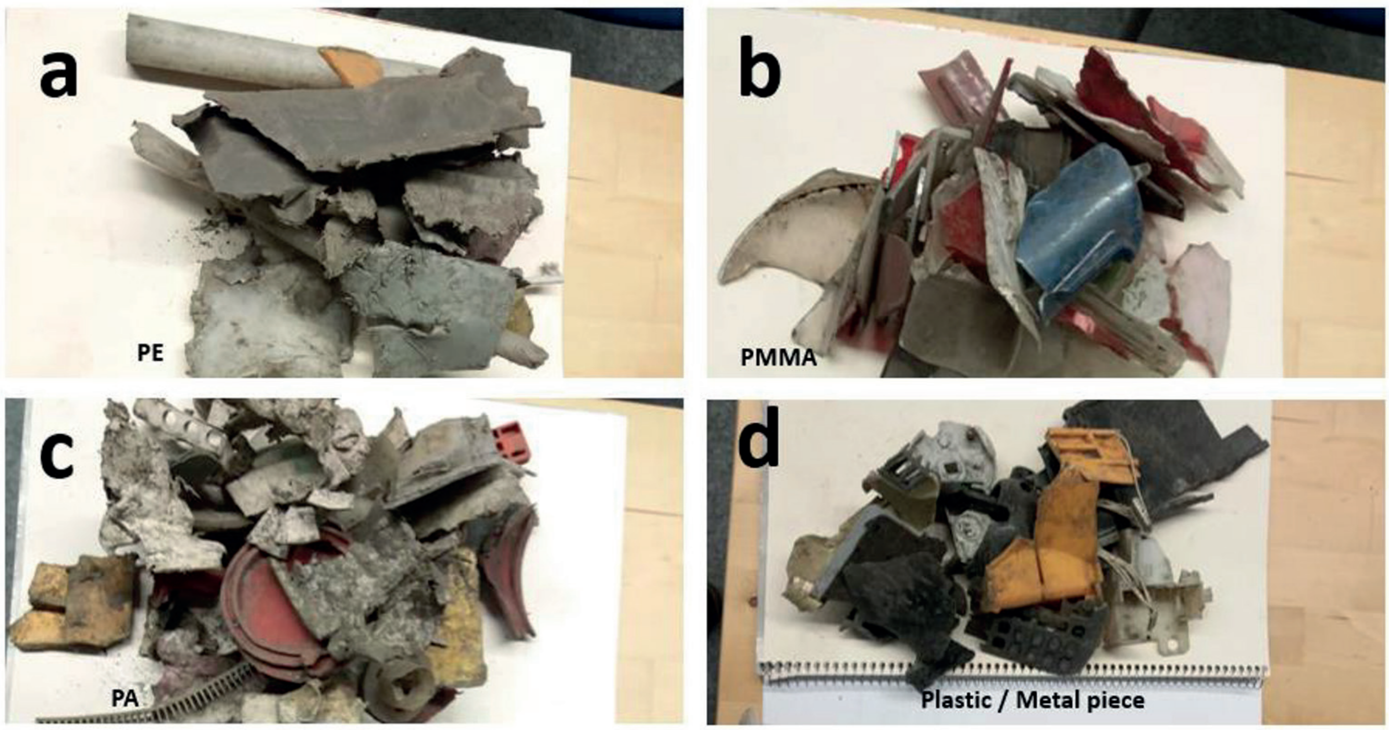

Figure 19. Examples of bromine-free plastics (a) PE, (b) PMMA, (c) PA, (d) Plastics/ metal pieces.

Description

The main aim of this sub-task was to determine the possibilities for recyclability and processing of waste plastics from electric devices in order to demonstrate the reusability and properties of the mixed plastics. Two types of electronic waste were sorted and separated (bromine-free electronic waste and brominated electronic waste) with the NIR spectroscopy technique. NIR spectroscopy was able to accurately identify 17 different types of material in both types of electronic waste, which amount to 60% of the material in the electronic waste. A nondestructive analytical method SEM-EDS was used to perform the experiment to determine the presence of elements in the electronic waste samples. The second aim was to study what is the appropriate processing method and processing parameters for WEEE plastics.

Results

The visually observed differences between the bromine-free electronic waste and the brominated electronic waste from the bulk material was that bromine-free electronic waste mainly contains few unwanted materials such as foams and rubber-like materials, whereas brominated electronic waste contains electrical wires, printed circuit boards (PCB), insulation materials and films. Similarly, the unidentified plastics were 90% black or dark-coloured plastic, and the remainder are mixtures of transparent, contaminated plastics or a mix of blended materials. The result obtained from the experiment validates the literature review showing the estimate and proportion ratio for the most common plastics used in WEEE, namely ABS, PC/ABS, PS, PP and PC. The respective proportions of these are 22%, 11%, 10%, 9% and 4%. In the processing of plastics, it was found that injection moulding was the most suitable method for processing of these plastics from the point of view of mechanical properties. It must be noted that process parameters such as temperature have a significant effect on the quality of the materials obtained. The properties obtained for ABS, PC-ABS and PS were optimal and almost comparable to virgin equivalents.

Bromine-free PP, PS ABS and PC/ABS samples were supplied by Kuusakoski Oy for further analysis. The grades are about the same as the ones that are used the most in electrical and electronics industry. The retrieved samples were washed and dried and then milled to an article size of about 2 mm. The milled plastic was then processed with a micro-compounder and micro injection moulding machine to test the tensile strength of the specimens. The specimens were tensile tested and tensile modulus, yield stress and strain at break were determined from the results. Comparison of the properties of the recycled WEEE plastics to number of virgin plastics of same grades are illustrated in Figure 20. As seen in the figures, the properties of the virgin plastics are distributed over quite wide range depending on the grade and application. The recycled plastics compare quite well to virgin plastics: the modulus is slightly higher, yield stress is about the same, and strain at break is typically slightly lower than for the virgin plastics. Decrease of the strain at break could be a sign of thermal degradation.

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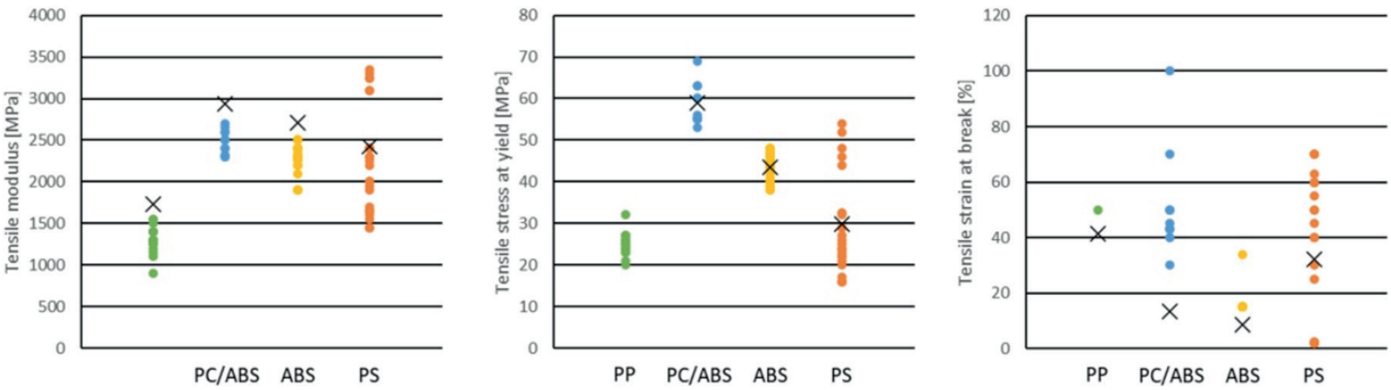


Figure 20. Comparison of tensile modulus, yield stress and tensile strain at break between recycled WEEE plastics (crosses) and virgin plastics (colour circles).

VALORISATION OF THE PROPERTIES BY MELT PROCESSING

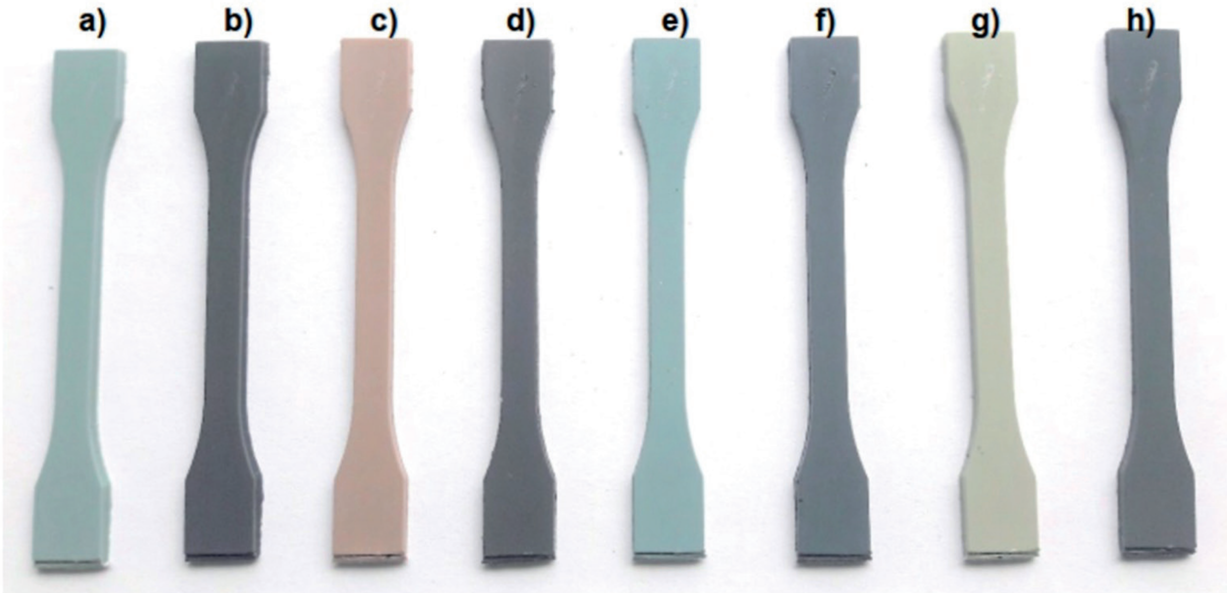


Figure 21. Examples of the tensile testing samples made with the micro injection moulding machine. The letters a and b indicate PP, c and d indicate PS, e and f indicate ABS, and g and h indicate PC/ABS. The letters a, c, e, and g indicate examples of the plastics with antioxidants, chain extenders, or without additives. The letters b, d, f, and h indicate examples of the plastics with graphene nanoplatelets grafted with maleic anhydride.

Description

Mechanical recycling of plastics is known to cause deterioration in their properties. Plastics can be subjected to harsh environments during both processing and service. These include exposure to mechanical loading, high temperatures, oxygen and moisture. Additionally, plastics can be subjected to light, radiation, and chemical reactions during use. All these variables can cause degradation of the polymer in various ways, such as changes in viscosity and the mechanical and aesthetic properties of the plastic. This study focused on ways to degrease the effect of the degradation by adding additives into the plastic during melt processing. The plastics included in the study were PP, PS ABS and PC/ABS. The additives were chosen based on a literature review. Two of the additives were antioxidants (Irganox 1010 (=AO 1) and Irganox 1076 (=AO 2)), two were chain extenders (Joncryl ADR 4400 (=CE 1) and Joncryl ADR 4468 (=CE 2)), and one was graphene nanoplatelets grafted with maleic anhydride (GM). The plastics and additives were first compounded with a micro-compounder with 0.5 and 1 wt% additive concentrations. The compounds were then injection moulded with a micro-injection moulding machine into rheometer and tensile test specimens. The tensile test specimens are illustrated in Figure 21. Finally, the effects of the additives were studied by way of tensile testing, viscosity measurements, and oxidation induction time (OIT) measurements.

Results

Due to device limitations, the measurement of OIT was possible only for PP and PS. The antioxidants improved the thermo-oxidative stability significantly, as both extended the oxidation time from 4.2 min to over 60 min for PP and from 2.0 min to over 60 min for PS already with 0.5 wt-% concentration.

Thermal degradation causes chain scission for all studied polymer grades leading to reduction in chain length. Antioxidants can help to maintain the chain length, but chain extenders and maleic anhydride grafted graphene nanoplatelets can potentially join the broken chains and increase the length. The effectiveness of the additive can be evaluated indirectly by measuring properties that are affected by the chain length, such as zero viscosity, which is directly related to chain length. The Table 8 shows the zero viscosities for different compounds. The milled sample is processed one time less than the others, so the difference between the milled and disc sample reveals the effect of the single processing cycle to the recycled plastic without any additives. The effect of the single cycle is modest for PP, PS and PC/ABS, but significant to ABS as the viscosity drops by 50%. The effect of the additives varies between the plastics. It seems that the antioxidants work for PP, PS and ABS, as the viscosity is kept close to the original level. Chain extenders have the highest impact on ABS, as the viscosity rises almost 300% with most of the compounds.

Additive	PP absolute (Pa*s)	PP milled (%)	PP disc (%)	PS absolute (Pa*s)	PS milled (%)	PS disc (%)
milled -	2215 ± 387	100	108	2833 ± 232	100	106
disc -	2050 ± 390	93	100	2680 ± 85	95	100
CE 1 0,5 %	1262 ± 275	57	62	2083 ± 83	74	78
CE 1 1 %	602 ± 48	27	29	2060 ± 30	73	77
CE 2 0,5 %	755 ± 77	34	37	2347 ± 68	83	88
CE 2 1 %	553 ± 33	25	27	2197 ± 81	78	82
AO 1 0,5 %	1910 ± 0	86	93	2327 ± 38	82	87
AO 1 1 %	1890 ± 20	85	92	2200 ± 10	78	82
AO 2 0,5 %	1895 ± 15	86	92	2300 ± 110	81	86
AO 2 1 %	2035 ± 125	92	99	2080 ± 10	73	78
GM 0,5 %	1430 ± 78	65	70	2373 ± 103	84	89

Additive	ABS absolute (Pa*s)	ABS milled (%)	ABS disc (%)	PC/ABS absolute (Pa*s)	PC/ABS milled (%)	PC/ABS disc (%)
milled -	29550 ± 1630	100	200	7283 ± 698	100	107
disc -	14744 ± 345	50	100	6785 ± 38	93	100
CE 1 0,5 %	34522 ± 14159	117	234	5947 ± 385	82	88
CE 1 1 %	44667 ± 8694	151	303	6460 ± 100	89	95
CE 2 0,5 %	40283 ± 1083	136	273	6329 ± 141	87	93
CE 2 1 %	42544 ± 4722	144	289	9778 ± 956	134	144
AO 1 0,5 %	17689 ± 2929	60	120	4722 ± 760	65	70
AO 1 1 %	13383 ± 650	45	91	3856 ± 21	53	57
AO 2 0,5 %	12050 ± 183	41	82	4193 ± 100	58	62
AO 2 1 %	13583 ± 817	46	92	4084 ± 75	56	60
GM 0,5 %	15300 ± 1310	52	104	6024 ± 546	83	89

Table 8. Zero viscosities for the compounds

The properties determined from the tensile test results were tensile modulus, yield strain, yield stress, strain at break and stress at break. The best correlation in change of the mechanical properties to changes in zero viscosities were observed in strain at break.

After small scale tests with DSM, a batch of bromine-free ABS reject from WEEE was tested on a larger scale in VTT´s mechanical recycling line (VAREX). This method is developed to retain the value of recycled plastic and the idea is based on inline viscosity measurements and control of the recycled materials, which allows maintaining or even upgrading the material properties by addition of specific polymers or additives to enhance the quality of recycled thermoplastics (Figure 22: The principle of the VAREX line).

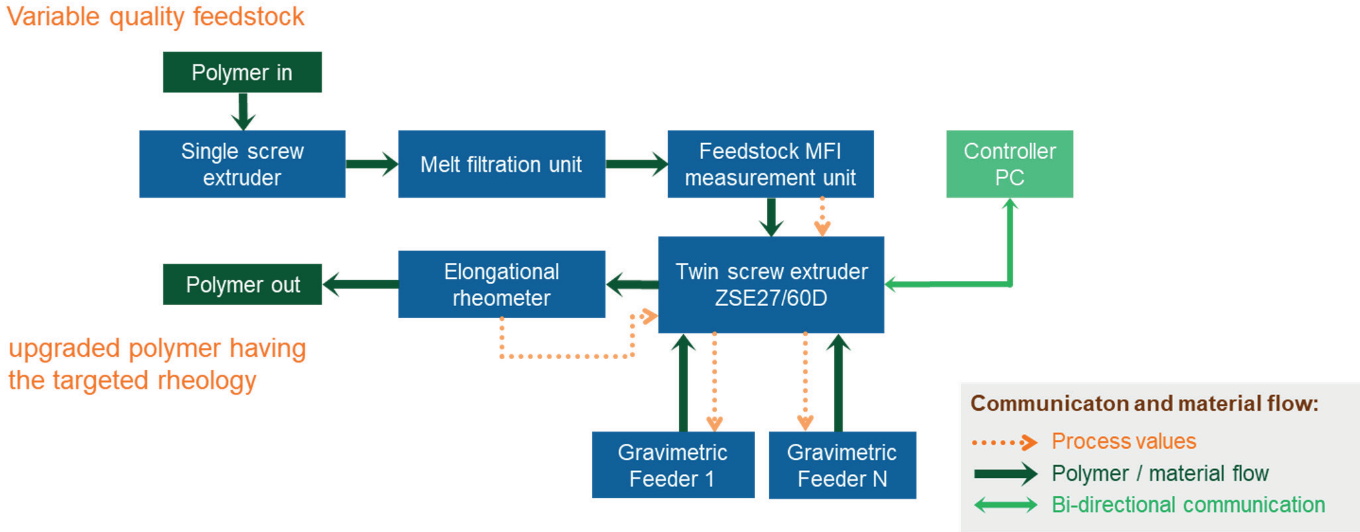


Figure 22. The principle of the VAREX line (Valorisation of waste plastics into valuable recycled plastics)

Newtonian viscosity

Code	Side extruder	Feeder 1	Feeder 2	Shear viscosity		Extensional viscosity
	r-ABS + 5% Igetabond	*ABS Cycolac MG47F*	*ABS Cycolac EX58F*	η_{S1} (Pa·s) @ 16.5 1/s	η_{S2} (Pa·s) @ 409 1/s	η_E (Pa·s) @ 7.6 1/s
PLASTIN-1	0	0	100	5845	404.7	162200
PLASTIN-2	0	100	0	**2963**	**318.4**	**120100**
PLASTIN-4	100	0	0	2671	259.2	97840
PLASTIN-5	50	25	25	3543	317.3	123600
PLASTIN-6: Target MG47F viscosity with 60% r-PP	**60**	**24.4**	**15.6**	**3186**	**301**	**121300**
PLASTIN-7: Set target to ηS1 = 3057 Pa·s, ηS2 = 263 Pa·s, ηE = 110250 Pa·s with maximum r-ABS content	**92.1**	**2.9**	**5**	**3079**	**287**	**110500**

Table 9. Base measurements for upgrading test trials of the r-ABS material (yellow) and VAREX-controlled tests (green: PLASTIN-6 and PLASTIN-7).

Firstly, viscosities of recycled and base material points were measured (Table A). The system was then commanded to produce material with a certain viscosity (comparable to commercial ABS MG47F = PLASTin-2) with a minimum of 60% recycled content. The VAREX controlling resulted in upgraded r-ABS (PLASTin-6) to match very close to target viscosity properties: Figure 23.

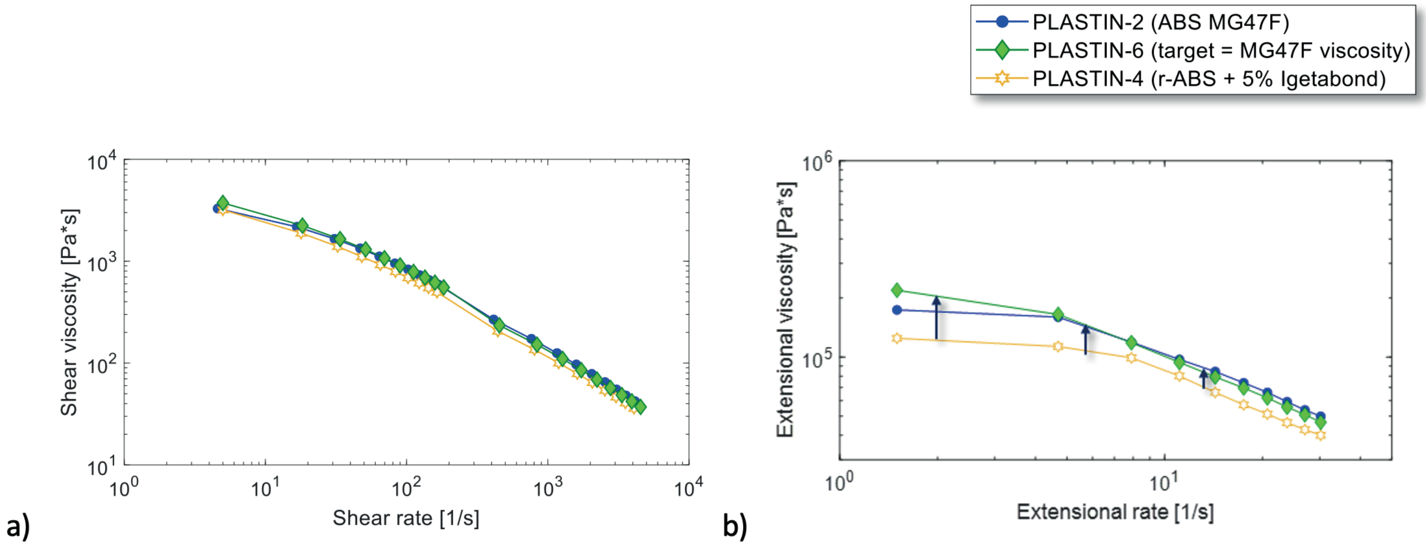


Figure 23. r-ABS viscosity upgrade at 60% recycled content: a) shear viscosity b) extensional viscosity

The compounds were further injection-moulded to produce 'dog bone' bars. Impact tests were performed on these samples (notched). With effective addi-tivation, impact strength was increased significantly compared to r-ABS (PLASTin-3) and results were close to impact strength of MG47F (Figure 24).

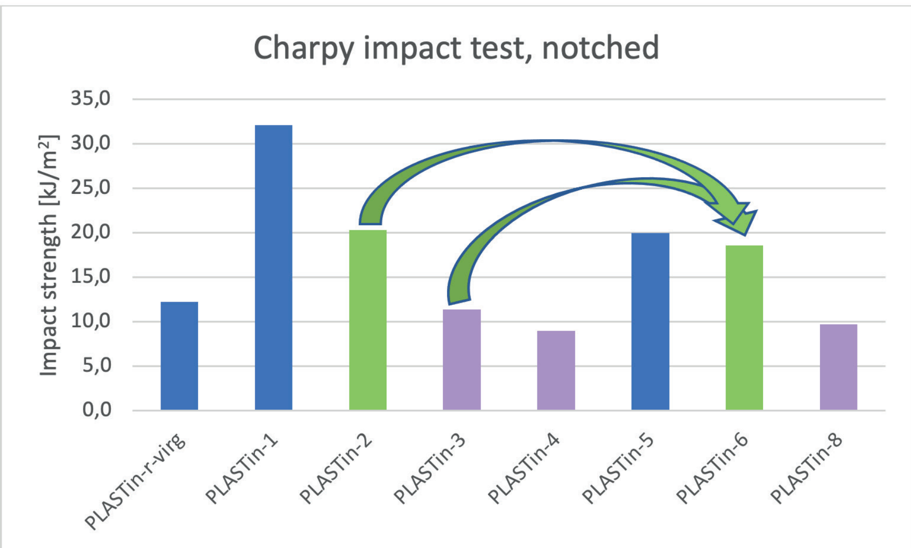
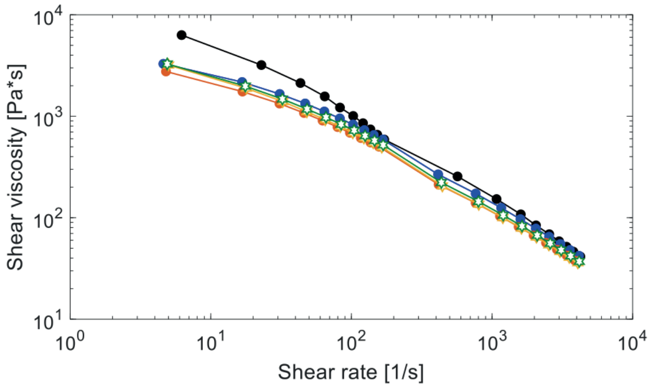


Figure 24. Impact strength of the samples produced with the VAREX line.



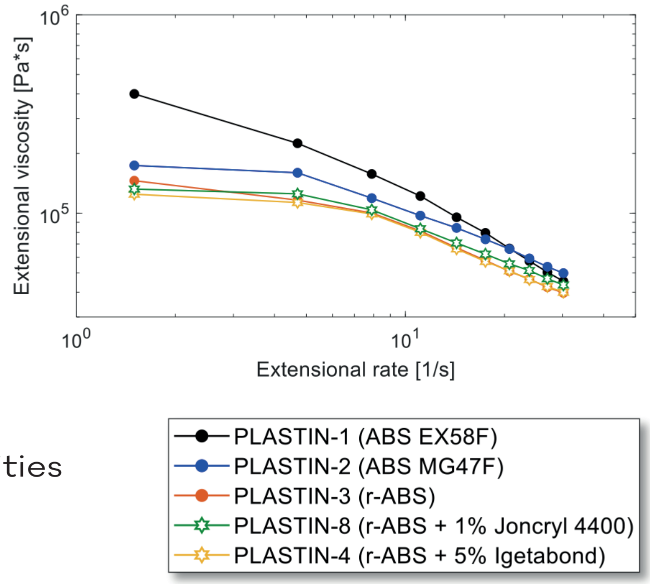


Figure 25. Effect of additives to r-ABS viscosities a) Shear viscosity b) Extensional viscosity.

Secondly the effect of two different type of additives were tested. The first one was chain extender (PLASTin-8), which had shown good results in earlier r-ABS tests and second one was supposed to increase the impact strength of the r-ABS. Secondly an epoxy-group containing Igetabond (PLASTin-4) was chosen to the test trials. Surprisingly, both additives reduced the viscosity of the compounds (Figure 25), as well as reducing impact strength (Figure 24, purple bars). The impact results are consistent to viscosity change, but the reason for reduction of viscosity and impact strength needs to be further investigated.

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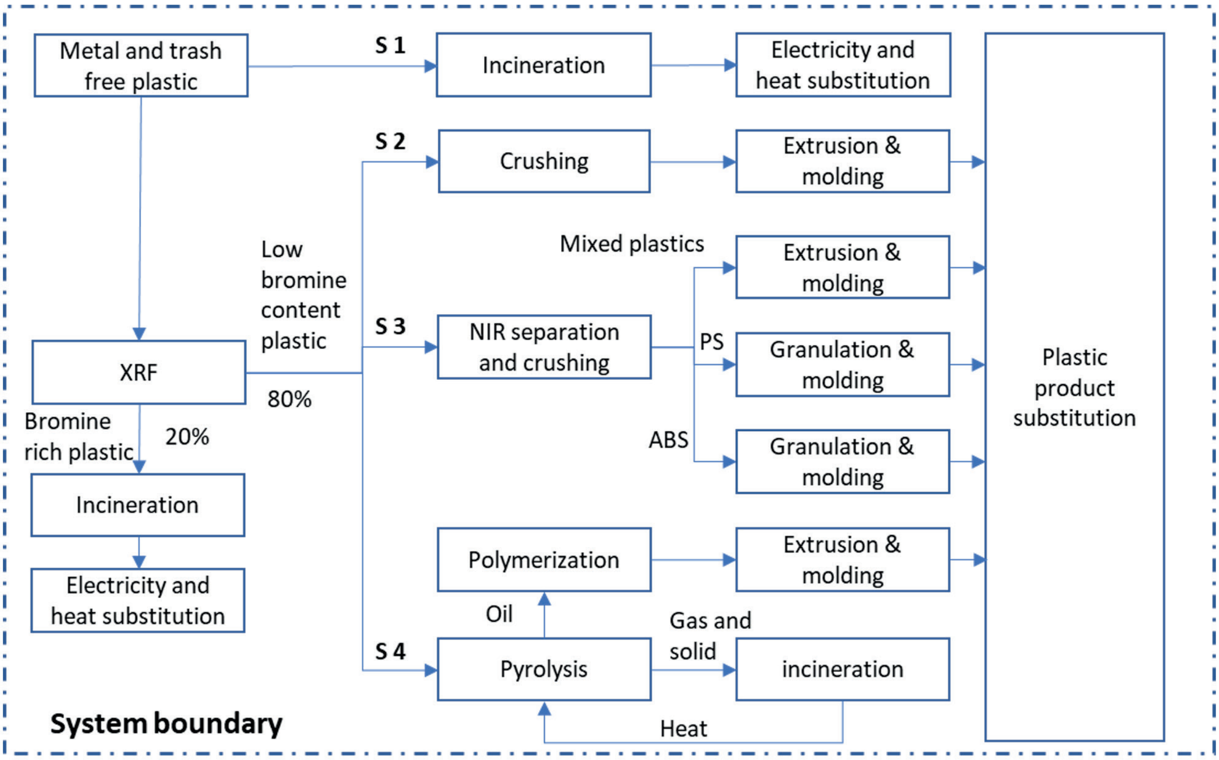

Figure 26. The main processes related to the studied scenarios S1 to S4 and the system boundary.

Description

The production of WEEE is increasing globally, and in 2016 it was estimated to be approximately 44.7 million tonnes (Baldé et al., 2017). The focus on WEEE treatment has been in recovering the valuable metals and the plastic fraction has mainly been directed to incineration. However, the plastic content in WEEE can range from 30 to 70% (Bachér et al. 2017), which could potentially be directed for recovery. Environmental performance analysis can provide information for considering the suitable treatment options by quantifying the potential environmental impacts and highlight the main processes contributing to that impact. To that end, the climate change-related impact of four different scenarios for WEEE plastic treatment options were analysed. The scenarios included incineration of WEEE plastics (S1) and three scenarios in which bromine-rich and bromine-free plastics are separated with XRF and bromine-rich plastic is directed to incineration, and bromine-free plastics are directed to mechanical recycling without separation of plastic grades (composite plastics) with NIR spectroscopy (S2), mechanical recycling with NIR separation (S3) and chemical recycling by pyrolysis (S4). The functional unit of the study is 1 tonne of metal-free and trash-free plastics from WEEE recycling, the main processes of the scenarios, and the system boundary are presented in Figure 26.

Results

The climate-related impacts of the studies scenarios are presented in Figure 27. According to the results, the current treatment of incinerating the WEEE plastic (S1) results to the highest net climate-related impact followed by chemical recycling by pyrolysis (S4) and mechanical recycling scenarios (S2 and S3). In scenario 1, the plastic waste incineration produces significantly more emissions compared to the benefits obtained from heat and electricity substitution resulting in a net impact on climate change. In scenarios 2 and 3, the net impact is negative due to the avoided emissions from product substitution. The incineration emissions are caused by the incineration of the bromine-rich plastic fraction. Scenario 3 has higher net emissions than scenario 2, due to the energy requirement of additional processes required for separating the plastic fractions. Scenario 4 has high emissions from the incineration, since in addition to the bromine-rich plastic being directed to incineration there are also other fractions which are directed to incineration, such as gas and char from pyrolysis. This also means that the avoided emissions from product substitution are more modest than in case of mechanical recycling, since part of the plastic waste sent for chemical recycling by pyrolysis is directed to incineration. In general, in terms of reducing emissions that contribute to climate change, mechanical recycling would seem to outperform the chemical recycling by pyrolysis. However, this is highly dependent on whether the quality of mechanically recycled plastics is high enough to substitute for other plastic usage. In addition, for example the char obtained from pyrolysis could potentially be used instead of directing it to incineration. The main finding seems to be that plastic waste should be directed away from incineration towards recycling, especially when the avoided emissions from energy substitution become lower due to the transition towards more renewable production.

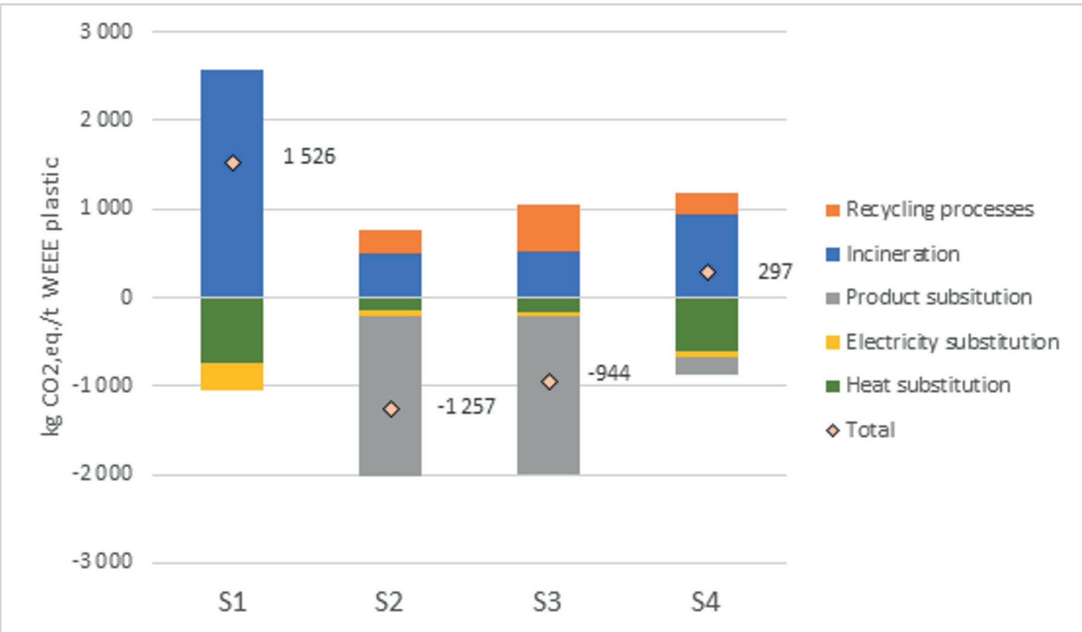

Figure 27. Climate change-related impact results of the four research scenarios (S1 to S4).

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