



ISSN 2278 – 0211 (Online)

Achieving a Smooth Surface Polystyrene Waste Recyclate in Hot-Melt Processing

Dr. Boniface Yeboah Antwi

Research Scientist, Materials and Manufacturing Division,
CSIR-Institute of Industrial Research, Ghana

Dr. Francis Boateng Agyenim

Director, CSIR-IIR Directorate,
CSIR-Institute of Industrial Research, Ghana

Daniel Ali Yidana

National Service Personnel, Sanitation and Environment Management Division,
CSIR-Institute of Industrial Research, Ghana

Jonathan Osei-Owusu

Lecturer, Department of Biological, Physical and Mathematical Sciences,
University of environment and Sustainable Development, Ghana

Albert Aniagyei

Head of Department, Department of Basic Sciences,
University of Health and Allied Sciences, Ghana

Ralph Kwakye

Lecturer, Department of Basic Sciences,
University of Health and Allied Sciences, Ghana

Abstract:

Polystyrene is an aromatic hydrocarbon plastic material with applications in the packaging, food, and construction industries. As a packaging material, it protects items against shocks and acts as an insulator in the construction of buildings and food preservation. The polystyrene bowl for food packaging has become a convention in the food and pastries industry in Ghana due to its clean, lightweight, and insulation properties. However, the corresponding waste litters its environment, chocks gutters, and does not decompose. For this reason, we explored the hot melt recycling technique to convert the PS wastes into valuable plastic plates that finds application in the artifact and souvenir industry. The incorporation of a 20% v/w lauric fatty acid (LFA) into the material matrix blocked micro holes in the finished product and induced a smooth surface. Characterizations included experiments such as Fourier Transform-Infra Red spectroscopy, melting point determination, tensile testing, and scanning electron microscopy (SEM). Generated data displayed the absence of a chemical bond between the PS molecules and the LFA additive. However, the methyl chains of the PS molecules were miscible with the saturated dodecyl chains of the LFA additive. Hence, the LFA additive was held in place by weak intermolecular forces between its chains and that of the PS molecules. The measured melting point of the recycled plastic with LFA content (rPS20) fell between 84-142 °C. Mechanically, the tensile strength dropped with the addition of LFA. The LFA induced a smooth surface morphology finishing in rPS20.

Keywords: Plastic wastes, recycling, polystyrene, plastic circular economy, and hotmelt recycling

1. Introduction

Plastic is a malleable and ductile material that can be obtained from the polymerization of monomers of the same or different kinds (Tsakona M. & . 2020). The over 380 million tonnes of plastics produced in a year (Ritchie H. & Roser., 2018) find applications in packaging, equipment parts, textiles, shoes, domestic wares, industry, furniture, and many more (OECD, 2018). The flexible, lightweight, durable, water-impermeable, non-corrosive, and poor degradability of plastics make them suitable replacements for glass, metallic and wooden products. Nonetheless, the use of these plastic products has contributed to an enormous amount of plastic waste (353 million tonnes in 2021) that is mismanaged and pollutes the environment (OECD, 2022). Aside from waste mismanagement, the production of virgin plastics from natural gas releases over 400 million tonnes of greenhouse gases annually into the atmosphere, which contributes to global warming (OECD, 2018). Hence, the global efforts at promoting sustainable production, use, and management of plastics in a circular economy (Shamsuyeva & Endres, 2021).

Ghana generates over 357,877 tonnes of plastic waste annually, of which 81% is mismanaged (Ritchie H. & Roser, 2018). Varied applications of plastics in the economic, social, and environmental sectors in Ghana have improved over the years. For instance, the availability of low-cost plastic dustbins, which substitutes metallic bins, enhances waste collection in homes, workplaces, and industries. Similarly, the replacement of paper bags and wooden baskets with polyethylene bags for carrying groceries has generated more jobs and promoted retailing businesses in Ghana (Blowplast, 1993). As a result, plastic waste is regularly generated with mismanagement, which requires the attention of stakeholders such as Municipal Assemblies, Researchers, Industry, and the Government.

Recycling is the conversion of recovered plastic material into new products (Hopewell J. et al., 2009), and has received lots of attention from industry in recent years, especially in developing economies, due to the associated prolonged, plastic life span and reduction in landfilling (Fobil J. N. & Hogarh J. N., 2006). Additionally, the recycling of plastics contributes to a decline in the volumes of virgin plastic monomers produced in a year and the number of harmful gases released into the atmosphere (OECD, 2018) in the process. Hence, it has the potential to protect the environment from further pollutions.

Amongst plastics that are commonly recycled are the polyethylene derivatives, such as low-density, high-density, linear low-density, and others (Kaiser et al., 2018). These materials find single applications in packaging, transport, electrical, construction, and other sectors, which make them readily available for recycling (OECD, 2018).

Recycling is categorized into four routes, they are, primary, secondary, tertiary, and quaternary recycling (Hopewell J. et al., 2009). The recycling of plastic wastes into the same virgin product becomes the primary recycling. An example is the recycling of polyethylene terephthalate (PET) bottle wastes into new PET bottles (Merrington, 2011). Secondary recycling, on the other hand, describes the recycling of plastic waste into new forms that have lesser properties compared to the original form (Elena, 2017). An example is the conversion of polyolefin wastes into dustbins. The breakdown of plastic wastes into constituent monomers and oligomers becomes tertiary recycling (Elena, 2017). The chemicals obtained can be converted into virgin polymers or serve as fuels in other chemical reactions (Merrington, 2011). For instance, the diols and dimethyl terephthalates for making new PET bottles are obtained from the glycolysis of old PET bottle wastes (Schlummer M. et al., 2017). Quaternary recycling is the Energy recovered from burning plastic wastes in an incinerator. For instance, the use of refuse-derived fuels is a quaternary recycling process (Yi-Bo Z. et al., 2018). The primary and secondary recycling techniques have widely been employed in industry and contributed to the current 18% global recycling rate (Yi-Bo Z. et al., 2018).

Polystyrene bowls like paper, cans and others are used in carrying fresh and cooked food products from vendors to offices and homes in Ghana (Ofosu-Okyere A. et al., 1997).

The plastic is widely used in packaging items and functions as a shock absorber or an insulator. For instance, it is an insulation material for packaging hot food and a shock absorber in packaging electrical parts. Chemically, the molecular structure is composed of an aromatic vinyl group monomer called styrene. It is hard, clear, and brittle at room temperature. It is easy to mold and remolds into different shapes as a thermoplastic polymer. Its melting point is 240°C, but it softens at 95°. It is produced on an industrial scale through extrusion, injection molding, and vacuum forming. The much-used form in Ghana is the injection molded takeaway bowls for packaging hot meals by food vendors, restaurants, and snack bars.

Even though it is recycled in other countries (Aciú et al., 2015), the reported methods are not easy to replicate in Ghana, a developing country with limited access to state-of-the-art technologies and financing to support the associated high investment capital. For example, EcoMENA in Riyadh, Kingdom of Saudi Arabia, recycles polystyrene through a four-stepped approach:

- Segregation,
- Compaction,
- Shredding,
- Melting/extrusion (Rubio, 2021)

This process requires an appreciable amount of investment in machinery. Hence, we explored low-cost Ghanaian recycling techniques to convert PS wastes into quinary materials of commercial value in the circular economy of plastics.

2. Methodology

2.1. Sample Preparation and Recycling

The virgin PS (VPS) waste bowls were collected from a plastic-only waste bin and washed thrice from food leftovers and other debris. The clean PS bowls were shredded into smaller pieces, dried at room temperature, and stored. The shredded PS sheets were baked in an oven at 240°C for 3 hours. The baked samples were removed from the oven and air-cooled for additional 2 hours, and the product was separated from the mold to obtain the recycled PS (rPS). The preparation of the rPS with 20% Lauric Fatty Acid (LFA) (rPS20) involved the crushing of a portion of rPS without LFA into granules. Then the 20% LFA was added and homogeneously mixed to form a paste. The paste was baked as described earlier. The product was then separated from the mould and kept for further characterization processes.

2.2. Functional Groups Determination

Conventional Fourier Transform-Infrared (FT-IR) spectroscopic method was employed to determine constitutional functional groups of VPS, rPS, LFA, and rPS20. Generated data were compared to literature functional groups of the chemical structures, as shown in figure 1.

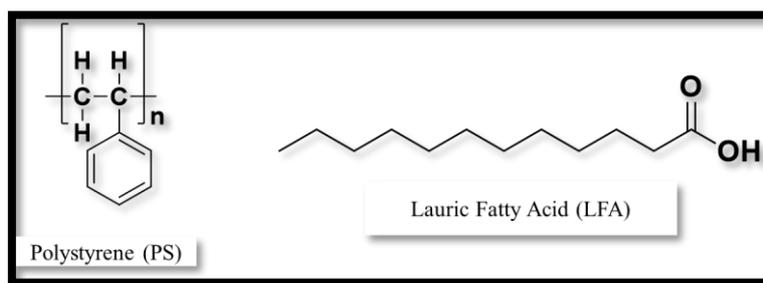


Figure 1: Chemical structures of PS and LFA

2.2.1. Melting Point

The melting point of products was determined by the conventional desktop method using the Stuart (Cole-Parmer) SMP10 Digital Melting Point Apparatus.

2.2.2. Tensile Strength

The ISO 6259-1 standard was followed to determine the tensile strength on a Hounsfield Universal tensile tester, Mode number H50ks. Five samples were prepared for each test, and the average was determined.

2.2.3. Surface Morphology

Scanning electron microscope EOL JSM-6390LV, at magnifications of 100X was employed in capturing the surface morphology of rPS and rPS20.

3. Results and Discussion

3.1. Functional Groups Determination

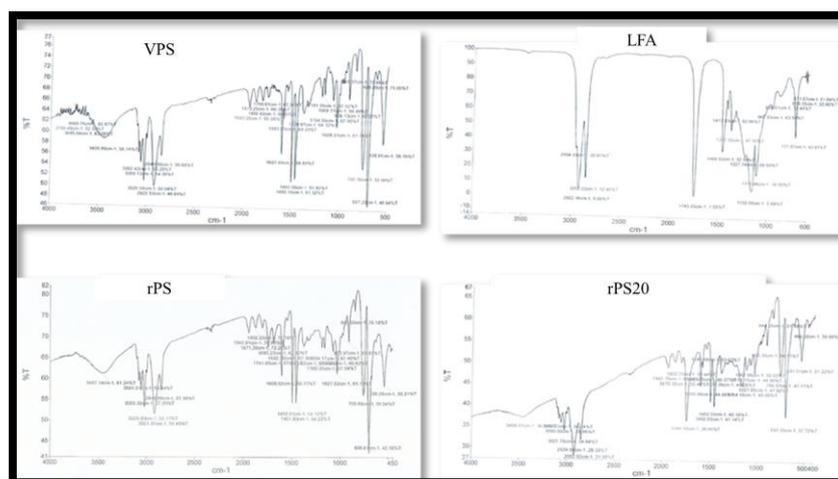


Figure 2: FT-IR Spectra of VPS, rPS, LFA, and rPS20

FT-IR measurement (Figure 2) displayed the presence of the characteristic phenyl group of polystyrene in the VPS, rPS, and rPS20, demonstrating the aromatic C-C stretch and C-H bends observed at 1600 and 755 cm^{-1} , respectively but shifted marginally downward from 1601.49 cm^{-1} of the VPS, to 1600.62 cm^{-1} and 1600.98 cm^{-1} in rPS and rPS20 respectively, Table 1. The LFA content was displayed at the ester peak position, 1744.15 cm^{-1} , in rPS20, which was a gentle forward shift from the 1743.25 cm^{-1} of the virgin LFA (see table 1). The rPS and rPS20 did not show any new peaks compared to the peak positions of the VPS and LFA. This indicates that the recycling process did not induce the formation of a chemical bond between the PS and LFA molecules. However, it is anticipated that weak non-bonding intermolecular interaction held PS and PLA chains together. Hence, the blended material, rPS20, will bear the synergistic properties of its constituents.

	VPS	rPS	LFA	rPS20	Functional Groups	Description
Peak Position (cm ⁻³)	3435.99	3467.14	-	3468.01	O-H stretch	Primary alcohol
	3025.98	3025.03	-	3025.70	C-H stretch	Aromatic
	2922.53	2921.65	2922.18	2924.06	C-H stretch	Alkanes
	2849.88	2849.86	2853.22	2852.92	C-H stretch	Alkanes
	1750.61	1741.65	1743.25	1744.15	C=O stretch	Esters, saturated aliphatic
	1601.49	1600.62	-	1600.98	C-C stretch	aromatic
	1493.15	1492.61	-	1492.83	C-C stretch	aromatic
	-	-	1465.53	-	C-H bend	Alkanes
	1452.58	1451.93	-	1452.55	C-H bend	Alkanes
	-	-	1377.55	-	C-H bend	Alkanes
	-	-	1155.65	-	C-O stretch	Tertiary alcohol
	-	-	1111.46	-	C-O stretch	Secondary alcohol
	1068.71	1068.31	-	-	C-O stretch	Primary alcohol
	755.36	755.68	-	756.37	C-H bend	Aromatic
	-	-	721.87	-	C-H rock	Alkane

Table 1: Spectra Positions and Description for Samples

3.1.1. Melting Point (MP)

	VPS	rPS	rPS20
Melting point range (°C)	141-152	131-152	84-142

Table 2: The Melting Point of the Virgin Polystyrene Melted Without LFA and with LFA

The melting point of VPS fell below the literature temperature of 160°C (Table 1) (Mehta et al., 1995), which is attributed to the presence of additive impurities. Similarly, rPS20 recorded a lower melting point range compared to rPS and VPS (Table 2). This was due to the presence of LFA impurities in the rPS, which caused a weakening of the intermolecular interaction between the PS chains. The presence of heat easily broke the bonds of rPS20 molecules with a corresponding enhancement in the molecular entropy that lowered the temperature at which the first and last crystals of the polymer melted.

On the other hand, the broader melting range of rPS20 (58°C) compared to the VPS (11°C) and rPS (21°C) (Table 2 and Figure 3) indicated that the LFA prolonged the complete melting of the rPS molecules in the blend through the melting of its unit alongside that of the rPS, while only the PS chains melted in VPS and rPS with minimal impurities and narrower range. Hence, as the impurity content increased, the melting range broadened, (Jo & Kwon, 1991).

The lower onset of the melting range for rPS20 is suitable for heat induced sculpture applications in the art and souvenir industry.

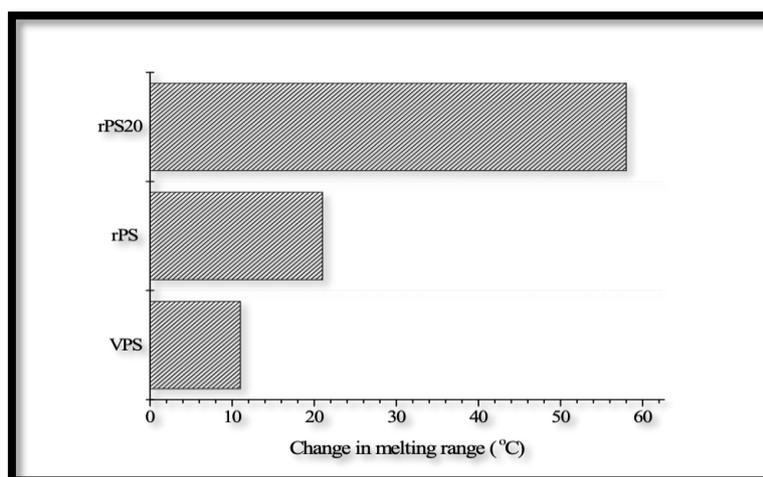


Figure 3: Melting Range Variations in PS Samples

3.1.2. Tensile Strength

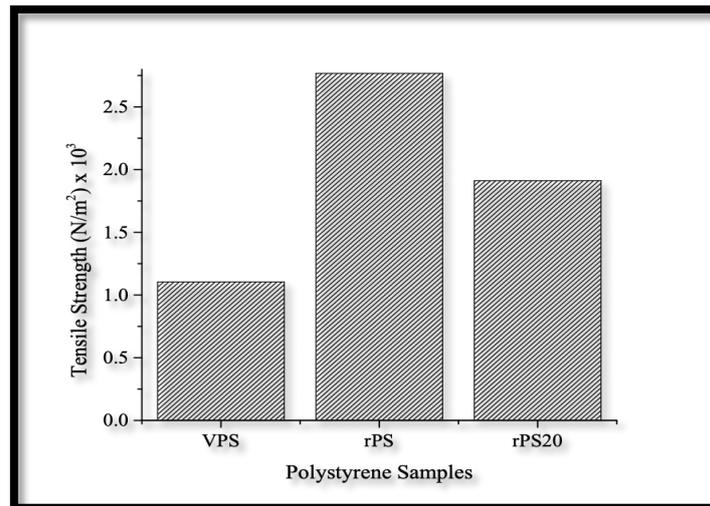


Figure 4: Tensile Properties for VPS, rPS, and rPS20

Mechanically, the rPS demonstrated a stronger tensile strength compared to VPS and rPS20 (Figure 4). This was attributed to the LFA acting as a diluent, reducing the strong intermolecular interaction of the PS material, and rendered it slightly loose and weak compared to the rPS molecules. In the case of VPS, its molecules had air trapped in between them during the expanding stage of its cold processing at the factory (Merrington, 2011); hence, the tensile strength was weaker than the rPS20 and rPS, whose units reoriented and closely packed during melt processing in the laboratory. The reduction in the mechanical strength of rPS in rPS20 confirms literature observations in other plastics, such as recycled polyethylene (rPE), with drop in impact strength when other polymer impurities were added to the matrix during recycling (Thoden van Velzen et al., 2021). Therefore, rPS20 will be suitable for applications that require minimal to no stress during use.

3.1.3. Surface Morphology

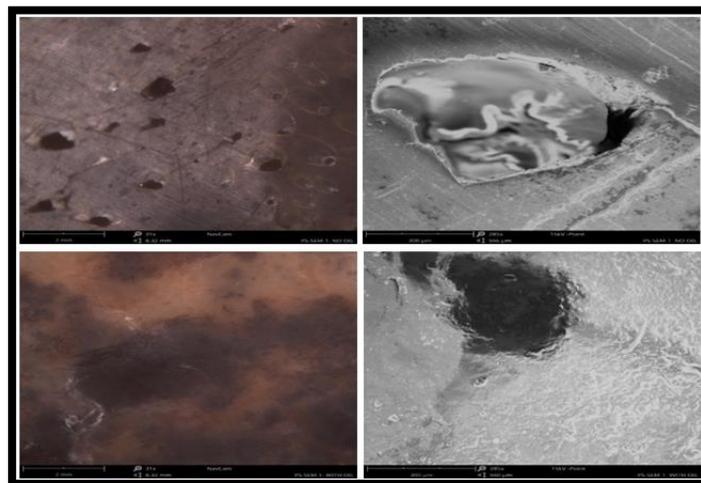


Figure 5: SEM Images of the Surface Morphology for rPS (Top) and rPS20 (Bottom)

The surface morphology of rPS, as shown in figure 4, top-left and right, had micro-voids, which were due to the irregular packing of the PS chains and trapped air in the starting VPS (Merrington, 2011). However, the micro-voids disappeared in the morphology of rPS20 with the presence of LFA (figure 5: white patches bottom-left and black patch bottom-right). This indicates that LFA sealed the micro-voids and induced a smooth surface morphology in rPS20.

The absence of cracks in the processed material indicated a favorable adhesion between the LFA and PS molecules (Hong-Ru L. & Chang-Tay, 1999), which demonstrates that LFA was a suitable additive for improving the surface morphology of rPS. The inherently smooth surface of rPS20 advances the commercial viability for applications in sectors that require low-cost product finishing.

4. Conclusion

The quinary recycling of plastics was achieved at an induced electrostatic interaction between PS and the carefully selected LFA molecules for improved recyclates with applications in the manufacturing of panels, floor tiles, and bench

tops. We have demonstrated the recycling of polystyrene bowl wastes into inherently smooth surface plastics for enhanced applications.

The material rPS20 demonstrated good mechanical strength, moderate resistance to heat above (100 °C), and a smooth surface, reported for the first time. The novelty will subsequently advance scientific research in the property modification of recycled plastics for sustainable circular economy.

5. References

- i. Aciu, C., Manea, D. L., Molnar, L. M., & Jumate, E. (2015). Recycling of Polystyrene Waste in the Composition of Ecological Mortars. *Procedia Technology*, 19, 498-505. <https://doi.org/https://doi.org/10.1016/j.protcy.2015.02.071>
- ii. Blowplast. (1993). *Companies and affiliated plastic products*. Blow Group of Companies. Retrieved on: 20/01/2022, from: <http://www.blowgroup.com/>
- iii. Elena, G. M. (2017). Methods of Recycling, Properties, and Applications of Recycled Thermoplastic Polymers. *Recycling*, 2(4), 24. <https://doi.org/10.3390/recycling2040024>
- iv. Fobil J. N., & Hogarh J. N. (2006). The dilemmas of plastic wastes in a developing economy: Proposals for a sustainable management approach for Ghana. *West African Journal of Applied Ecology*, 10(1), 1-8. <https://doi.org/10.4314/wajae.v10i1.45716>
- v. Hong-Ru L., & Chang-Tay, L. (1999). Mechanical Properties and Morphology of Recycled. Plastic Wastes by Solution Blending. *Polymer-Plastics Technology and Engineering*, 38(5), 1031-1050. <https://doi.org/10.1080/03602559909351629>
- vi. Hopewell J., Dvorak R., & Kosior E. (2009). Plastics recycling: challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526), 2115-2126. <https://doi.org/doi:10.1098/rstb.2008.0311>
- vii. Jo, W. H., & Kwon, I. H. (1991). Equation of state theory for melting point depression in miscible polymer blends. *Macromolecules*, 24(11), 3368-3372. <https://doi.org/10.1021/ma00011a050>
- viii. Kaiser, K., Schmid, M., & Schlummer, M. (2018). Recycling of Polymer-Based Multilayer Packaging: A Review. *Recycling*, 3(1), 1-26. <https://doi.org/10.3390/recycling3010001>
- ix. Mehta, S., Biederman, S., & Shivkumar, S. (1995). Thermal degradation of foamed polystyrene. *Journal of Materials Science*, 30(11), 2944-2949. <https://doi.org/10.1007/BF00349667>
- x. Merrington, A. (2011). 11 - Recycling of Plastics. In M. Kutz (Ed.), *Applied Plastics Engineering Handbook* (pp. 177-192). William Andrew Publishing. <https://doi.org/10.1016/B978-1-4377-3514-7.10011-X>
- xi. OECD. (2018). Improving Plastics Management: Trends, policy responses, and the role of international co-operation and trade. *OECD Environment Policy Papers*, 12, 1-21. <https://doi.org/doi:https://doi.org/10.1787/c5f7c448-en>
- xii. OECD. (2022). *Plastic pollution is growing relentlessly as waste management and recycling fall short, says OECD*. OECD Environment. Retrieved 4/6/2022 from <https://www.oecd.org/environment/plastic-pollution-is-growing-relentlessly-as-waste-management-and-recycling-fall-short.htm#:~:text=Global%20plastic%20waste%20generation%20more,11%25%20from%20clothing%20and%20textiles>.
- xiii. Ofosu-Okyere A., Ellis W.O., Oldham J.H., & I., O. (1997). Review of some packaging materials/ Techniques used in Ghana. *Journal of the University of Science and Technology, Kumasi.*, 17(3), 13-19.
- xiv. Ritchie H., & Roser, M. (2018). *Plastic Pollution*. Retrieved on: 22/01/2022, from: <https://ourworldindata.org/plastic-pollution>
- xv. Rubio, M. R. (2021). *Environment, Recycling, Waste Management*. EcoMENA. Retrieved on: 04/08/2022, from: <https://www.ecomena.org/polystyrene-wastes/#:~:text=Recycling%20Trends&text=At%20present%2C%20the%20recycling%20of,order%20to%20reduce%20its%20volume>.
- xvi. Schlummer M., Maurer A., Wagner S., Berrang A., Fell T., & F., K. (2017). Recycling of Flame Retarded Waste Polystyrene Foams (EPS and XPS) to PS Granules Free of Hexabromocyclododecane (HBCDD). *Advances in Recycling & Waste Management: Open Access*, 2(2), 1-5. <https://doi.org/10.4172/2475-7675.1000131>
- xvii. Shamsuyeva, M., & Endres, H.-J. (2021). Plastics in the context of the circular economy and sustainable plastics recycling: Comprehensive review on research development, standardization, and market. *Composites Part C: Open Access*, 6, 100168. <https://doi.org/https://doi.org/10.1016/j.jcomc.2021.100168>
- xviii. Thoden van Velzen, E. U., Chu, S., Alvarado Chacon, F., Brouwer, M. T., & Molenveld, K. (2021). The impact of impurities on the mechanical properties of recycled polyethylene. *Packaging Technology and Science*, 34(4), 219-228. <https://doi.org/https://doi.org/10.1002/pts.2551>
- xix. Tsakona M., & R. I. (2020). *Report requested by the Secretariat of the Basel Convention for the first meeting of the Basel Convention Plastic Waste Partnership*. GRID-Arendal. https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_document/554/original/UNEP-CHW-PWPWG.1-INF-4.English.pdf?1594295332
- xx. Yi-Bo Z., Xu-Dong L., & Hong-Gang N. (2018). Solvent-based separation and recycling of waste plastics: A review. *Chemosphere*, 209, 707-720. <https://doi.org/10.1016/j.chemosphere.2018.06.095>