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Eco-Friendly Flame-Retardant Solutions: Repurposing Polystyrene Waste into Fire-Resistant Polymers

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Abstract:
The most common types of insulation are Expanded and extruded polystyrene are commonly known as EPS and XPS, respectively; for more than 50 years, both types have been manufactured with the brominated flame retardant hexabromocyclododecane (HBCDD). As soon as HBCDD was Stockholm Convention controlled it because it is a substance of high concern in addition to European REACh laws. As a result, HBCDD insulation is not recommended. Insulation manufactured with HBCDD-equipped EPS or XPS is being phased out, and its waste cannot further undergo cutting-edge mechanical recycling. Most of the EPS and XPS built before the ban on HBCDDs are still in service. Research is being conducted to find more complex methods of reusing insulating material. Polystyrene from insulation is dissolved in a solvent and recycled in this research. Waste and eliminate both the co-dissolved HBCDD and the insoluble waste components. Due to this procedure, the study examines the mechanical characteristics of regenerated PS and the efficacy of HBCDD removal. Inorganic waste and other non-target polymers were safely separated, and the results indicated an overall increase in purity, removing more than 99.6 per cent of the HBCDD that was there to begin with. Recycled polystyrene's mechanical characteristics are in the typical quantity of virgin general-use PS, provided that residual solvents are removed if the recycled polymer has a residual solvent level of less than 0.1%, and then it may be used.

Keywords: PS, XPS, EPS, wasted, polystyrene, solvent.

1-Introduction

Expanded polystyrene (EPS) as well as extruded polystyrene (XPS) products have gained significant traction in the global construction and packaging industries.

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Both materials possess stability and low specific weight, making them suitable for insulating applications and for use in the packaging of food and other consumer goods. Exterior thermal insulation composite systems (ETICS) are a convenient insulation material used in building construction and repair, and EPS is a key component of these systems. The European Union of Polystyrene Producers (EUMEPS) was founded in 2011. released data indicating that the packaging business in Asia produced over 1.3 million tonnes of EPS annually, while Europe produced approximately 1 million tonnes. The market for Expanded Polystyrene (EPS) in building applications is estimated to be 1.3 million tonnes annually in Europe and Asia. (Schlummer, 2017)

The management of EPS and XPS trash generated from packaging has been effectively implemented since these materials are often discarded immediately after use and are well addressed by existing waste packaging collection and return systems. To the flip side of , building waste generates very limited quantities of waste XPS and EPS. (Troya, 2022)

There are two primary factors contributing to this phenomenon. Firstly, most insulating panels remain intact and have not been removed. Secondly, polystyrene (PS) is mostly not separated from mixed demolition trash and is not exposed to recycling processes. (Aksit, 2019)

PS foams are commonly used components in the recycling of polystyrene (PS) on an industrial level. (Turner, 2020)

EPS recycling efforts primarily focus on managing and treating discarded EPS packaging materials. The abovementioned activities are executed using mechanical procedures, including compression, grinding, and re-compounding. EPS derived from building debris is often employed in lightweight concrete and render manufacturing processes. The complexity of recycling technology increases when post-consumer trash is treated due to the presence of various pollutants. The contaminants included in the sample encompass substances such as cement and glue, sticky tape, and food residues. (An, 2017)

One significant challenge associated with recycling EPX and XPS materials is transporting them to the designated treatment facilities, given their large volume and deficient weight. Hence, the compaction of waste material is the most advanced technology in this field. Seo and Hwang comprehensively evaluated appropriate technologies, including techniques such as moulding, mechanical compaction, and solvent application. In the presence of solvents, further processing is carried out using recycling methods based on solvents and polymers. (Voith, 2022)

Since the fiscal year 2014/2015, an additional impediment has emerged in recycling extruded polystyrene (XPS) and expanded polystyrene (EPS) derived from building debris. Due to regulatory restrictions, flame retardants are necessary for the building application of XPS and EPS materials. Historically, hexabromocyclododecane (HBCDD) was widely used as the preferred flame retardant for Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS), commanding a worldwide market dominance of 95%. In 2008, the European Union designated HBCDD as a Substance of Very High Concern (SVHC) because of its PBT characteristics: persistence, bioaccumulation, and toxicity. Consequently, HBCDD was subsequently included in Annex XIV of the REACH Regulation 2011. The manufacture and use of HBCDD in PS foams inside the European Union (EU) is contingent upon submitting an authorization application by August 2014, followed by the issuance of temporary permission by the European Chemicals Agency (ECHA) and the European Commission. The addition of HBCD to Annex A (Elimination) of the Stockholm Convention's list of persistent organic pollutants (POP) occurred on 9 May 2013. (Ghoshal, 2023.)

The ruling signifies the prohibition of both the manufacturing and use of HBCD. An application may be made for a time-limited exemption to produce and use PS foams in constructing structures. (Nukmal, 2018)

In response to these legal advancements, a specialized polymeric brominated flame retardant (PolyFR) has been developed to substitute HBCDD in polystyrene foam used for building and construction purposes. (Jeanne, 2016)

Nevertheless, it is anticipated that during the next two to five decades, the waste expanded polystyrene (EPS) and extruded polystyrene (XPS) derived from building and demolition activities will exhibit substantial quantities of hexabromocyclododecane (HBCDD). (Aminot, 2020)

Under prevailing regulations, the only approved method of managing trash containing HBCDD is by its annihilation. Nevertheless, a potential and more environmentally friendly strategy would include the extraction of HBCDD from the polystyrene matrix, resulting in the retrieval of flame-retardant-free polystyrene that may be used in novel applications. If flame retardants are isolated, they may be used as a secondary bromine source, provided they are in an appropriate condition for the specific recovery technique. (Knutsen, 2021)

As previously documented, the CreaSolv® technique has been successfully used to separate brominated flame retardant chemicals from polystyrene. The solvent-based recovery method uses secure solvent formulations to dissolve a specific polymer (PS or EPS) from a waste stream and separate it from any remaining undissolved substances. Additionally, it becomes possible to separate brominated flame retardants from the surrounding material via extractive cleaning. This results in the production of pure granules of the desired polymer following the recovery of solvents. The practical application of the CreaSolv® technique to waste EPS was observed in 2004. However, the investigation and resolution of HBCDD removal have not been thoroughly examined recently.

Furthermore, the performance of the CreaSolv® process has been enhanced due to two recently concluded research projects, namely PolyRessource and PolySOLVE. The project yielded two primary outcomes: an enhanced extractive cleaning technology and a refined solvent recovery technique. (Rani, 2017)

This study aims to provide up-to-date empirical evidence about recycling expanded polystyrene (EPS) containing hexabromocyclodecane (HBCDD). The emphasis is placed on eliminating HBCDD in laboratory settings and on a smaller technical scale. Furthermore, this study aims to evaluate and analyze the mechanical characteristics of recycled polystyrene (PS) to establish the potential impact of an enhanced CreaSolv® process on the qualities of the recycled material.

2-Literature review

The growing apprehension over environmental sustainability and fire safety has prompted the investigation of novel approaches that effectively tackle both concerns concurrently. An example of a potential solution is the creation of environmentally sustainable flame-retardant materials by the use of discarded polystyrene, which may be transformed into fire-resistant polymers. The use of polystyrene, a frequently employed polymer, poses significant environmental concerns owing to its inherent non-biodegradable nature and the possibility of emitting toxic substances upon combustion. Researchers and industry endeavor to develop a more sustainable method for fire safety by integrating polystyrene waste into fire-resistant polymers, therefore avoiding further contributions to plastic trash. (Li et al., 2022)

The use of polystyrene in packaging, insulation, and other consumer goods is prevalent owing to its advantageous characteristics of being lightweight and possessing insulating capabilities. Nevertheless, the proper disposal of this substance is a substantial environmental dilemma. Conventional approaches to waste management, such as the practice of depositing waste in landfills or subjecting it to burning, are implicated in the exacerbation of plastic contamination and the subsequent emission of hazardous substances into the surrounding ecosystem. Given these circumstances, the prioritization of discovering inventive methods for repurposing polystyrene trash has emerged. (Li et al., 2020)

The use of discarded polystyrene as a valuable raw material for the production of fire-resistant polymers has been a primary area of interest among researchers. The transformation of polystyrene waste into a flame-retardant additive may be achieved via the use of chemical modifications and processing techniques. Subsequently, this additive may be integrated into diverse polymer matrices in order to augment their fire-resistant characteristics. These altered polymers possess the potential to be used in several sectors such as building materials, textiles, electronics, and other businesses that prioritize fire safety. (Zhao et al., 2022).

3-Benefits of using environmentally sustainable flame-retardant solutions:

The benefits of using environmentally sustainable flame-retardant solutions: (Liu et al., 2022)

- The repurposing of polystyrene trash leads to a significant decrease in the environmental impact associated with its disposal. This strategy aligns with the concepts of the circular economy by reducing the need for fresh plastic manufacture and mitigating the buildup of plastic trash.
- The fire resistance of polymers may be improved by the integration of flame-retardant additives obtained from polystyrene waste, hence enhancing fire safety. Ensuring effective fire prevention measures is of utmost importance in mitigating the fast propagation of flames and minimizing associated fire-related risks.
- Resource efficiency is shown by the exploitation of polystyrene waste as a flame-retardant additive, since it allows for the extraction of value from a waste stream that would otherwise contribute to environmental degradation.

The promotion of innovation and collaboration is facilitated by the advancement of environmentally friendly flame-retardant solutions, fostering cooperation among researchers, industry, and policymakers in order to effectively tackle urgent environmental and safety issues.
The adoption of sustainable solutions by companies may facilitate regulatory compliance and enable them to satisfy customer expectations in light of increasingly stringent environmental restrictions. (Yuan et al., 2022)

4-Challenges and Future Directions

Although the recycling of polystyrene waste into fire-resistant polymers shows potential advantages, there are still obstacles that need to be addressed. Further research and development is necessary in order to provide consistent flame-retardant performance, preserve material integrity during processing, and ensure the scalability of the proposed technology. (Chen et al., 2019)
In next years, there is a strong likelihood that more research will be directed towards the enhancement of fire-resistant polymer formulations, assessment of their enduring environmental consequences, and the advancement of economically viable manufacturing techniques. Furthermore, the involvement of academic institutions, enterprises, and governmental organizations will be crucial in expediting the implementation of these environmentally friendly flame-retardant technologies. (Shi et al., 2021)
The use of discarded polystyrene material for the production of fire-resistant polymers serves as an example of a proactive strategy in tackling environmental issues and meeting fire safety standards. Industries may make significant contributions to a more environmentally friendly future and prioritize the safety and welfare of persons and communities by effectively using cutting-edge technology and adopting sustainable practices. (Gao et al., 2021)

5. Methodology

5.1 Materials

5.1.1 PS foams

Samples of polystyrene (PS) foams derived from demolition trash were collected on-site at a demolition location. The plaster was removed on-site, but traces of adhesive and mortar remained inside the substance. The waste material used in this study was sourced from Sunpor, a prominent European manufacturer of expanded polystyrene (EPS) and extruded polystyrene (XPS) products in the post-industrial sector. The acquisition of Stryrolution PS 156 F, a pristine polystyrene (PS) variant used in manufacturing PS foams, was made by Biesterfeld Plastic GmbH. Table 1 enumerates the many PS foam types, pollutants, and associated additives.

Table 1sample collection

Sample	Specifications	Genesis	Implementation
Waste EPS	Construction debris foam.	Austria.	Laboratory weighing trials
Waste XPS	Sunpor's extruded XPS debris from an industrial setting.	Austria	Laboratory scales of technological miniature
Virgin GPPS	Styrolution makes Styrolution F156, which may be converted into XPS.	Germany	mall technical scale

5.1.2 Solvents:

From CreaCycle GmbH in Grevenbroich, Germany, we ordered two different solvent formulations: Creasolv® PS and Creasolv® PSF. For PS foams, people utilized Creasolv® PS, which was a solvent, and Creasolv® PSF, which was an anti-solvent.

CreaSolv® is a registered brand of CreaCycle GmbH in Grevenbroich.

Tetrahydrofuran, ethanol, and acetone analysis grades were obtained by Merck (Darmstadt, Germany) to solve analytical problems.

6. Method

6.1 Integrative recycling methodology

The CreaSolv® technique is used to extract polystyrene (PS) from waste materials that consist of PS foam. The use of patented CreaSolv® PS formulations is employed, which have been determined to not pose any significant hazards following the EU Regulation (EC) No. 1270/2009 (CLP/GHS). PS foams, EPS, and XPS are dissolved in the disintegrating unit after being treated with a solvent formulation. A mechanical solid-liquid separator is used to purge the polystyrene (PS) solution of impurities such as dirt, cement, adhesive, metals, and foreign polymers. The insoluble substance is subjected to a drying process in order to reclaim the solvent for further usage within the process. The Persistent Organic Pollutants (POPs) inventory includes the brominated flame retardant HBCDD. However, removing HBCDD from polystyrene (PS) cannot be achieved by mechanical means alone since it requires an extracted purification process. The extractive clean was removed to remove the dissolved hexabromocyclodecane (HBCDD) from a precipitated polystyrene (PS) gel. The present in the PS gel is extracted during polymer drying. This process enables the retrieval of over 99% of the solvent and yields recovered PS granules. These materials have the potential to be used in the manufacturing processes of General general-purpose polystyrene (GPPS), Extruded Polystyrene (XPS), or Expanded Polystyrene (EPS). A solvent recovery unit and the process reclaim the solvents extracted from HBCDD. The inert material is handled as POP-free demolition waste, while the soluble HBCD portion is used for bromine recovery.

6.2 Laboratory-scale investigations

Samples B and Cng between 10 and, consisting CreaSolv® PS was used to treat scrap expanded polystyrene (EPS) & extruded polystyrene (XPS) from manufacturing and consumer sources. Concrete and mortar, both of which are insoluble, were separated in the lab using sedimentation and coarse filtering techniques.

The use of extractive cleaning methods achieved the elimination of HBCDD. Consequently, an anti-solvent was introduced into the polymer solution that had undergone filtration, creating an extract phase and polymer gel. This latter component was anticipated to consist mainly of the HBCDD substance isolated from the gel. A sequential extractive cleaning was conducted to enhance the degree of purification. The gel or extract phases were weighed at each purification step, and X-ray fluorescence (XRF) spectroscopy was performed on sub-samples taken from both phases. Processing extraction-cleaned gels made of polymer in an enclosed oven for 4 hours yielded solvent-dried polystyrene (PS) grains. Using vacuum extrusion on a laboratory scale, we could remove all traces of the solvent.

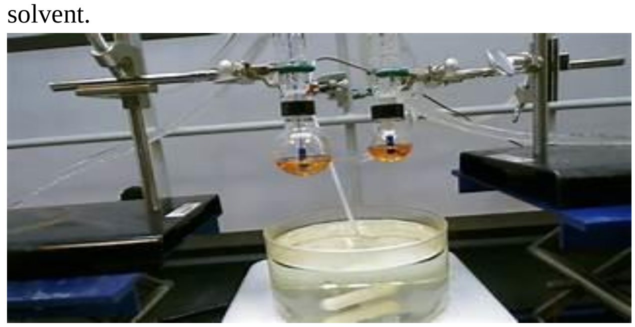

Fig. 1 CreaSolv® PS was used to treat scrap expanded polystyrene (EPS) & extruded polystyrene (XPS)

6.3 Microscopic technological processes

A 14-kilogram polystyrene (PS) sample, derived from post-industrial waste XPS, was generated using the small-scale CreaSolv® unit located at the Fraunhofer Institute IVV. The waste material underwent a coarse crushing before dissolving in CreaSolv® PS inside a 100 L reactor with stirring and jacket heating. Following the dissolution process, the XPS sample underwent filtration using a 100 µm filter and underwent a multi-step extraction procedure to eliminate HBCDD.

After the gels were filtered and extracted, they were removed from the solutions and anti-solvents in a drum with a swirling jacket. Using a vacuum pump was used to provide a vacuum, resulting in the condensation and trapping of solvent vapours. The vessel capacity was used to discharge intermediate PS products, which were then subjected to analysis in order to determine their residual solvent concentration.

The final drying process was conducted by an external collaborator using a specialist extrusion line. The capacity of the extrusion line is 40kg/h. The present aggregate showed superior drying efficiency compared to a smaller-scale drying method employed in the European PolySOLVE project that had a 3kg/h capacity. The degassing line's modified temperature gradient and screw design are likely responsible for this improvement.

Fig. 2 drying process using degassing line's

6.4 Researching the Properties of Materials

Differential Scanning Calorimetry (DSC) was used to probe the glass transition temperature. The Mettler Toledo DSC 821 instrument was used to take the readings, and the sample was heated from 25 degrees Celsius to 140 degrees Celsius at a rate of 10 degrees Celsius per minute.

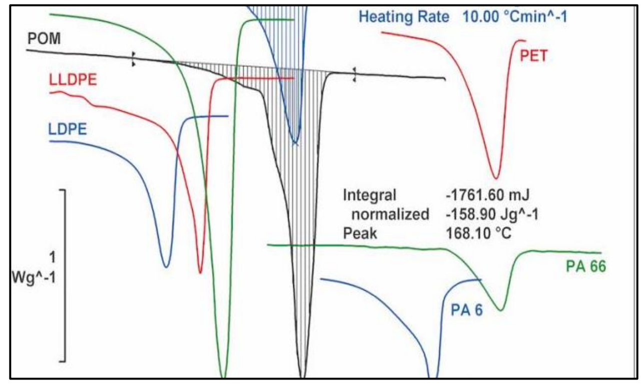

Figure 3 Mettler Toledo DSC 821

Gel permeation chromatography (GPC) was used to calculate molecular weights (Mw) following the DIN 55672-1 standard. The polystyrene (PS) samples were dissolved in 2500 ppm tetrahydrofuran (THF) and filtered through 0.2 m polytetrafluoroethylene (PTFE) syringe filters before being measured.

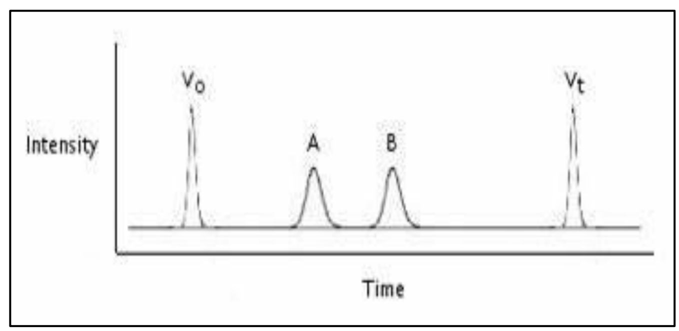

Fig. 4 GPC for molecular weight

The measurement was done using a Dionex ASI-100 automated sample injector, a Gynkotex Model 300 high-precision pump, an Erma ERC3612 degasser, and a Spark Holland Mistral column oven. The measurement temperature was 40 degrees Celsius, and THF was employed as the mobile phase in conjunction with two GPC columns (5 m, 8*300 SDV, linear M). The detection process was carried out using a refractive index detector (UVD 340S, Gynkotek). In order to perform calibration and analysis, we used narrowly dispersed polystyrene (PS) standards that were dissolved in tetrahydrofuran (THF).

Fig. 5 Dionex ASI-100 automated sample injector, a Gynkotex Model 300 high-precision pump, an Erma ERC3612 degasser, and a Spark Holland Mistral column oven.

The Melt Flow Indices (MFI) were determined following ISO 1133 using a CEAST modular MFI instrument with a test temperature of 200°C and a test weight of 5 kg. The samples were conditioned under the DIN EN ISO 291 standard and conducted tensile tests per the DIN EN ISO 527-2 standard. The Charpy impact strength was evaluated under the DIN EN ISO 179-1 standard.

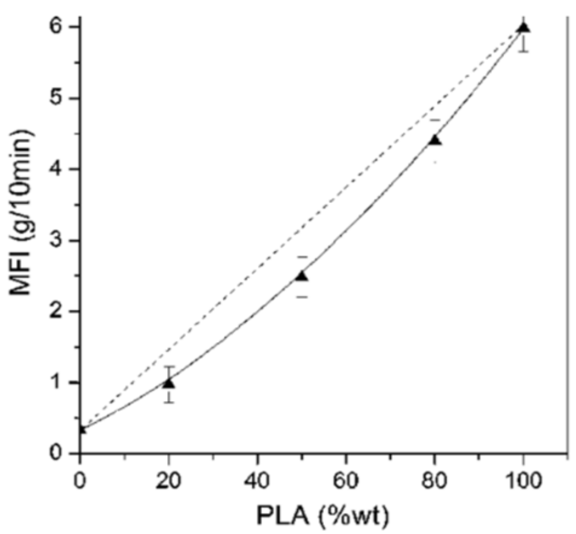

Fig. 6 Melt Flow Indices (MFI) were determined following ISO 1133 using a CEAST modular

The residual solvent quantities in intermediate and end products were assessed using headspace gas chromatography and a flame ionization detector (HS-GC-FID). The notion of repeated headspace injection served as the basis for quantification.

6.5 Analysis of bromine and HBCDD:

In this work, X-ray fluorescence (XRF) analysis was used to determine the concentrations of bromine and hexabromocyclododecane (HBCDD). The Spectro Spectrolab 2000, a desktop energy-dispersive X-ray fluorescence (XRF) instrument, was used to analyze bromine. After adding extracts and polymer gels, Prolene® films were used to seal the XRF cups (made by LGC, Germany). The XRF autosampler was used to analyze both samples for bromine, and standard calibration procedures were followed.

Through the use of LC-MS, the remaining traces of hexabromocyclododecane (HBCDD) in both the final products and the starting materials were determined. Ten percent of the regenerated PS was dissolved in tetrahydrofuran (THF). After that, we added five times as much ethanol (EtOH) to the mixture to get it to precipitate. The PS gel supernatants were filtered through a 0.45 m PTFE syringe filter and analyzed by LC/MS. Analyses using LC/MS were performed using a Waters QuattroLC instrument.

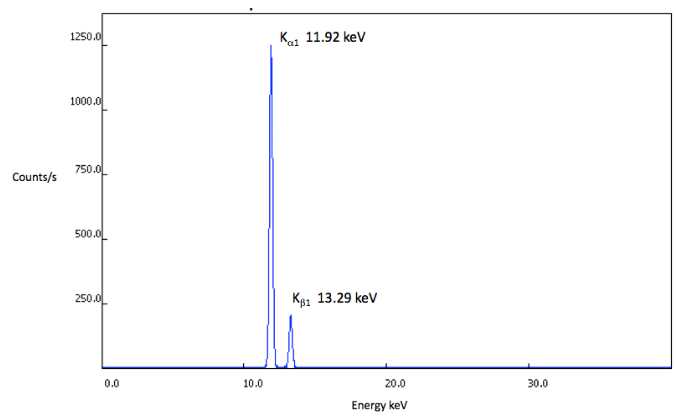

Fig. 7 XRF spectrum of bromine

7. Results and discussion

7.1 Laboratory scale research

Laboratory-scale research was conducted to examine the processes of dissolution and mechanical cleaning.

Dissolving and cleaning:

The effective dissolving of EPS and XPS was achieved using a unique solvent formulation, CreaSolv®, applied at a temperature much below its flash point, as stated in Patent EP 1438351 B1. Hence, the liquid substance may be effectively used for dissolution in recycling facilities operating on an industrial scale. It can also be employed in outdoor settings such as demolition sites.

Initially, mechanical methods removed undissolved materials from dissolved EPS and XPS. The specific samples under investigation heavily influence the quantity of insoluble material. In contrast, undissolved chemicals (like Sample B) are typically required in the waste EPS and XPS panels collected from building construction sites. Exterior thermal insulation composite systems (ETICS) made from recycled waste EPS, however, cannot be re-used after they have been dissolved. contains mortar, glue, and fabric (Sample C). The EPS solutions provided by ETICS underwent a process of sedimentation followed by filtering for purification. The undissolved substance exhibited no interaction with the CreaSolv® liquid. To effectively manage the volume of liquid involved, implementing a surface drying and solvent recovery unit would be necessary in a production-scale operation to facilitate the recycling process.

7.2 Extractive cleaning

The CreaSolv® formulation liquid effectively co-dissolves HBCDD, rendering it inseparable from PS solutions by mechanical methods. Therefore, a cleaning method that relies on the concept of dissolution and precipitation was selected, known as an extractive cleaning strategy. A solvent with anti-solvent properties was introduced to the mechanically purified polystyrene solutions, forming a biphasic system consisting of the polystyrene gel and the extract.

The initial dissolved polystyrene (PS) concentration was systematically manipulated throughout a broad spectrum in laboratory-scale experiments. Following the first precipitation, each polystyrene gel was subjected to several extractions. In order to assess the effectiveness of the cleaning process, the quantities of bromine in both the extract and the polystyrene gel were analyzed using X-ray fluorescence spectroscopy (XRF). Since HBCDD was considered the only origin of bromine in the material under investigation, the presence of bromine is assessed as an indication of HBCDD. The hexabromocyclododecane (HBCDD) levels were determined by calculating the bromine levels, assuming that HBCDD contains 75% bromine. The constancy of the distribution of HBCDD across the two stages facilitated the development of a computational model for a multi-step cleaning process. Consequently, the developed model has the potential to forecast the necessary quantity of consecutive extraction procedures for a particular initial concentration of HBCDD, aiming to achieve a reduction of HBCDD levels by 99.9-99.7% to a threshold below 100 ppm (as shown in Table 2).

Table 2: The concentrations of hexabromocyclododecane (HBCDD) in laboratory-scale products.

	Starting level Ppm	Product concentration ppm	Purification %
Waste EPS/XPS	17000	38	99.9%
Scrapped XPS	16000	57	99.7%

7.3 Limited Technical Outcomes

7.3.1 Chemical dissolving and mechanical scrubbing

The technical application of CreaSolv® to the issue of dissolving polystyrene (PS) or PS foams exhibits notable distinctions. Nevertheless, it is possible to produce polystyrene solutions using several feedstocks.

Mechanical cleaning machines designed to remove dissolved polystyrene (PS) using sedimentation and filtering principles are primarily influenced by the composition of the waste material.

7.3.2 Getting treatment for HBCDD

As assessed by XRF, small-scale technical demonstrations using extractive cleaning resulted in a progressive decrease in HBCDD levels in extracted PS gels. Once again, the calculated amounts were consistent with the observed levels in extracts and gels. This demonstrates that studies of the extraction process conducted at a laboratory size might be accurately replicated at a smaller technical scale.

Based on XRF fluorescence measurement, the HBCDD concentration in the PS gel after extraction reached 48 ppm.

This indicates the degree of purity achieved in the laboratory, which is 99.8 per cent.

7.3.2 Recovering the solvent while drying

Drying the product is essential to effectively separate the solvent from the recycled polystyrene (PS) and to facilitate the recovery of the solvent for further use within the overall process. In order to achieve the desired outcome, thermal energy and a state of low pressure were used. During our experimentation with pristine polystyrene (PS), we achieved a concluding concentration of solvent residue at 900 parts per million (ppm). The residual solvent content of recycled goods derived from waste XPS reached levels as low as 700 ppm.

Additionally, solvents were retrieved from the extracts obtained during the HBCDD elimination procedures. The polymer concentration in these stages is relatively low, allowing a significantly accelerated drying process. Due to the lack of detailed specifications for the following bromine recovery unit interface, the drying process was halted when the dry matter content reached a range of 40-60%. The thick liquid by-product would undergo further drying to provide a far more solid product.

7.3.3 Mechanical characteristics of a product

Table 3 displays the qualities of laboratory-size items, whereas Table 4 presents the properties of small technical outputs.

The anticipated range for the glass transition temperature of pristine polystyrene (PS) falls between 99 and 106°C. The Tg levels of partially dried PS measurements are much lower, but both thoroughly dried samples demonstrate glass transition temperatures slightly above 99°C.

The recycled polystyrene (PS) derived from virgin PS, with a melt flow index (MFI) of 35g/10min, shows an MFI of 73g/10min after partial drying, approaching the MFI of virgin PS after the entire drying process (35g/10min). The melt flow index of the end product derived from waste XPS exhibits a slight decrease.

The molecular weight of polystyrene (PS) remains unchanged throughout the recycling process and subsequent stages. The observed findings exhibit variations within the specified measurement tolerance of 11%. The MFI value, which demonstrates no substantial change between the input material and the recycled polystyrene (PS), provides more support for this finding. The molecular weight of the plastic significantly influences the viscosity of the melt.

Implementing an improved configuration of screw and temperature profiles led to a notable improvement in the performance of the extrusion line, leading to a residual solvent content of less than 8 parts per million (ppm). The end products exhibited a glass transition temperature (Tg) of 102 °C, which closely aligns with the Tg of the original polystyrene (PS) input material. This may be attributed to the minimal residual solvent content present in the final products.

Furthermore, the MFI, molecular weight analysis and Charpy impact tests did not indicate any substantial degradation of characteristics compared to the original material (input material). The results indicate that to get a high-quality recycled polystyrene (PS), it is essential to have a residual solvent content below 900 parts per million (ppm).

Nevertheless, once this criterion is met, recycled polystyrene (PS) exhibits similar qualities to virgin PS.

Table 3: A comparative analysis of the chemical characteristics of laboratory-size products and their corresponding input materials.

Sample	Mw	PD	Residual solvent
Dimension	g/Mol	Dalton	%age
Input	177.230	313	-
Input, crushed	176.380	282	-
Intermediate PS gel	196.803	190	Approx. 51
Dried Intermediate PS product	196.893	187	3
Vacuum-dried PS products	197.008	218	0.263

Table 4 Comparison of the chemical characteristics of fresh GPPS, recycled GPPS, and recycled PS derived from XPS

Sample	Tg [°C]	MFI [g/10 min]	Solvent content [ppm]	Molecular weight [g/mol]	Charpy impact test [kjm-2]
Newly created GPPS (Styrolution PS 156 F).	103	36	-	146003	6± 1.09
Recyclate from GPPS in the middle stage (about 96% dry matter).	55	73	50000	144945	-
Recycled GPPS	104	35	900	141055	6.5 ± 1
XPS scrap	-	-	-	175534	-
intermediate recyclate from XPS (~98% dry matter)	72	-	30000	177722	-
Recycled PS from XPS	106	25	700	170237	-

8. Conclusion:

8.1 CreaSolv® Technology's degree of technical preparedness

Establishing an appropriate recycling method for PS foam was conducted over an extended duration due to addressing several technological obstacles. The fundamental concept of dissolving polystyrene (PS) from expanded polystyrene (EPS)/extruded polystyrene (XPS) waste streams and the extractive removal of hexabromocyclododecane (HBCDD) was previously established in 2004. Nevertheless, at that period, the process cost and the end product quality did not meet the necessary standards for industrial expansion. (Drage, 2018)

Additional processing advancements were made by using other polystyrene (PS) sources, including waste electric and electronic equipment (WEEE). The ultimate technological challenge was developing a durable and cost-effective drying method. This method was not readily accessible in the market and required original development efforts until 2012. The novel drying approach was subsequently evaluated within the framework of the European PolySOLVE project. This study used environmentally friendly solvents derived from natural sources instead of CreaSolv® formulations. The final products obtained from the PolySOLVE demonstration experiments did not meet the necessary product standards, mainly owing to inadequate drying. The causative factor behind this phenomenon remained ambiguous since it was uncertain whether it stemmed from solvent-polymer interactions of a particular kind or from technical difficulties. (Schlummer, Advances in Recycling & Waste Management: Open Access., 2017)

On the other hand, the drying experiments conducted in this research used an enhanced drying method, mainly using a more advanced extrusion line. The implementation of this approach resulted in a considerable reduction in the quantity of residual solvent present in the final goods.

Indeed, it is worth noting that each stage of the CreaSolv® idea has been meticulously devised and tested in a laboratory setting before being successfully implemented on a smaller technological scale. Based on the principle of technological readiness, it is seen that a TR level of 7 is indicated. Therefore, the logical stages in further study and demonstration of the CreaSolv® process would include installing and operating a pilot prototype. (Zabrocki, 2016).

8.2 Utilizing CreaSolv® Technology for the Disposal of Used PS Foams

First and foremost, recycling materials from polystyrene foams consistently faces competition from other treatment methods, namely incineration. Furthermore, it should be noted that both incineration and the CreaSolv® process are just components of the whole solution. Before undergoing treatment, it is necessary to gather and transport PS foams containing HBCDD from various locations where waste is generated, such as demolition and refurbishment sites that are spread out. The standard method of garbage collecting often involves the first step of shredding the waste material to a coarse consistency, followed by a separation process to remove any foreign substances such as cement, mortar, glue, and similar materials. Additionally, foams are often compressed to enhance the overall density of the waste. One potential avenue for innovation may include the use of solvent tanks for collecting materials, which would then be subjected to a process of solid-liquid separation to remove any foreign substances. This process would facilitate the segregation of polystyrene (PS) and hexabromocyclododecane (HBCDD) from mineral scrap, ensuring that the mineral scrap is free from HBCDD. This separation would occur outside of the CreaSolv® factory. The solvent tanks in question are designed to accumulate expanded polystyrene (EPS) from collection stations throughout the area until the viscosity of the polystyrene (PS) solution exceeds a certain threshold. Subsequently, the polystyrene (PS) solution would be transported to a centralized CreaSolv® facility for further processing.

Treatment of bromine-rich products is necessary downstream from the CreaSolv® process. We propose using a bromine recovery unit as a potential alternative to the secure disposal of this fraction in a hazardous waste incineration facility. This suggestion is based on the absence of catalytically active (heavy) metals, such as copper, within this fraction. Ultimately, the reclaimed bromine may be valuable in producing novel polymeric brominated flame retardants, including PolyFR, currently used in treating EPS and XPS materials.

The recycling process involves using discarded PS foams to generate two significant components that may be used to manufacture new XPS. Specifically, recovered PS serves as a viable alternative to general-purpose materials. The present study investigates the use of polymeric brominated flame retardant PolyFR as a bromine source in a polystyrene (PS) matrix with an extended molecular length. The proposed methodology is an encouraging illustration of the sustainable principle of a circular economy.

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