H2020-SC5-2018-2: PLASTICS TO BE CLEANED BY SORTING AND SEPARATION OF PLASTICS AND SUBSEQUENT RECYCLING OF POLYMERS, BROMINE FLAME RETARDANTS AND ANTIMONY TRIOXIDE

D6.13 ROUTE MAP FOR RECOMMENDATIONS TO THE CONSORTIUM AND THE STAKEHOLDERS ACROSS THE WHOLE VALUE CHAIN

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1. Terms, definitions and abbreviated terms

Abbreviated Terms			
Acronym	**Definition**	**Acronym**	**Definition**
ATO	Antimony trioxide	Mw	Molecular weight
BFR	Brominated flame retardants	DfR	Design for Recycling
TRL	Technology Readiness Level	WEEE	Waste Electrical & Electronic Equipment
EEE	Electrical & Electronic Equipment	WP	Work Package
ABS	Acrylonitrile Butadiene-Styrene	XRF	X-ray fluorescence spectroscopy
rABS	Recycled ABS	PPO	Polyphenylene oxide
vABS	Virgin ABS	HIPS	High Impact Polystyrene
LCA	Life Cycle Assessment	ATEX	Atmospheres Explosible
POP	Persistent Organic Pollutants	LCC	Life Cycle Costing
SVHC	Substance of High Concern	NIR	Near-infrared spectroscopy
PC	Polycarbonate	FTIR	Fourier-transform infrared spectroscopy
REACH	Registration, evaluation and authorization of chemicals	SoA	State of the Art

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2. Executive Summary

PLAST2bCLEANEDs aim is to develop a recycling process for Waste of Electrical and Electronic Equipment (WEEE) plastics in a technically feasible, environmentally sound and economically viable manner. To fulfil this aim, PLAST2bCLEANED addresses the recycling of the most common WEEE polymers, acrylonitrile butadiene styrene (ABS) and high impact polystyrene (HIPS), that contain up to 20wt% brominated flame retardants (BFR) and up to 5wt% of the synergist antimony trioxide (ATO). PLAST2bCLEANED will close three loops: (1) polymer, (2) bromine (Br), and (3) ATO.

This document is the project deliverable D6.13 and includes a route map for recommendations to the consortium and the stakeholders across the whole value chain.

PLAST2bCLEANED contains several Work Packages (WP). Each WP has created valuable insights and derived recommendations to the stakeholders across the value chain. Those recommendations are explained in detail in this report and the key recommendations are summarised below:

- Invest in further testing of higher Technology Readiness Level (TRL) of the PLAST2bCLEANED technologies.
    - Improve and scale-up the sorting technology of waste plastic into further sub-fractions to reach the purification target and filter out contaminants at an early stage of the recycling process. This is crucial as to increase the percentage of recycled content in products.
    - Use advanced NIR, FTIR and Raman sensor-based classification lines to sort plastics.
    - On demo plant level, specifically testing with real ABS (90-95% purity) waste. Further research is needed to scale up the dissolution technology to recycle ABS, bromine and ATO (current TRL is 5).
    - Engineering companies are recommended to create a more continuous set up instead of batch-wise processing whilst keeping Atmospheres Explosible (ATEX) type of operation in mind.
- Improve the performance of products: Improve decoloration of recycled ABS (rABS) or limit visibility of rABS in product uptake to make it more attractive to end-users. The performance of recycled plastic is similar to virgin ABS (vABS) if polymer producers add stabilizer and butadiene rubber (important for engineering companies).
- Inform and create awareness of the real environmental and health impact of recycled material by comparing the environmental or health benefit compared to vABS.
- Assess the costs of plastics created using the PLAST2bCLEANED route into more detail during the various scale up steps.
- Support the legislation and research around the eco-design of products and Design for Recycling (DfR). Concrete recommendations are:
    - For designer of EEE: choosing the right colorants for plastic components that do not interfere the sorting or by the development of standard labels that allow the identification of this type of waste through optical sorting.
    - For chemical companies as well for engineering companies: consider using additives that will not affect the recycling or technical properties of the recycled material.
- Standardise the Registration, Evaluation and Authorization of Chemicals (REACH), Persistent Organic Pollutants (POP) and Substance of very high concern (SVHC) tests of

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DfR products to lower or take away the barrier of market entry of products that are manufactured with recycled materials.

- Implement policy and economic instruments for emission-based accounting such as CO_2 tax, regulations or crediting scheme. The PLAST2bCLEANED route realises emission reduction; those instruments would stimulate the attractiveness of rABS from this route.

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3. APPROACH

All partners of the PLAST2bCLEANED project were asked to give their recommendations. As presented in Figure 1, the consortium consists of six partners representing the whole value chain. Technology development is done by the research institutes TNO, Gaiker and Fraunhofer.

At the upstream side of the value chain are the recycling companies. Within PLAST2bCLEANED, the recycler Coolrec is involved, Gaiker is involved for development of the novel sorting technologies. As a second layer in the value chain, , producers of polymer and additives are presented: the chemical companies CAMPINE for the recycling of the ATO and and ICL for the BFR fraction , and ELIX for the recompounding of the polymers recovered. The dissolution based recycling technology is developed by TNO and Fraunhofer with the engineering support from Juchheim Laborgeräte. The downstream value chain is completed by end-users of the recycled products: Electrolux representing insights for end-users of the rABS in their electronic and electrical products.

The consortium set up and partners were well chosen to get a concise picture and to cover whole the value chain. In that way, insights from the complete value chain are covered. Within PLAST2bCLEANED, three loops are closed and the goal to increase the recycled plastic uptake can be fulfilled; the practical use case of uptake of recycled fractions in electric and electronic products (such as a washing machine door). The recycled ATO and Bfr can be used by chemical industry, thus reducing the demand of ATO and BFR.

The recommendations are clustered around the following type of stakeholder groups:

A. Stakeholders in the plastics value chain:

(1) recycling companies (such as COOLREC),
(2) chemical companies (such as CAMPINE and ICL);
(3) engineering companies (such as Juchheim);
(4) polymer producers (such as ELIX);
(5) end-user of recycled polymer (such as Electrolux);

B. Policy makers (6)

C. Investors (7)

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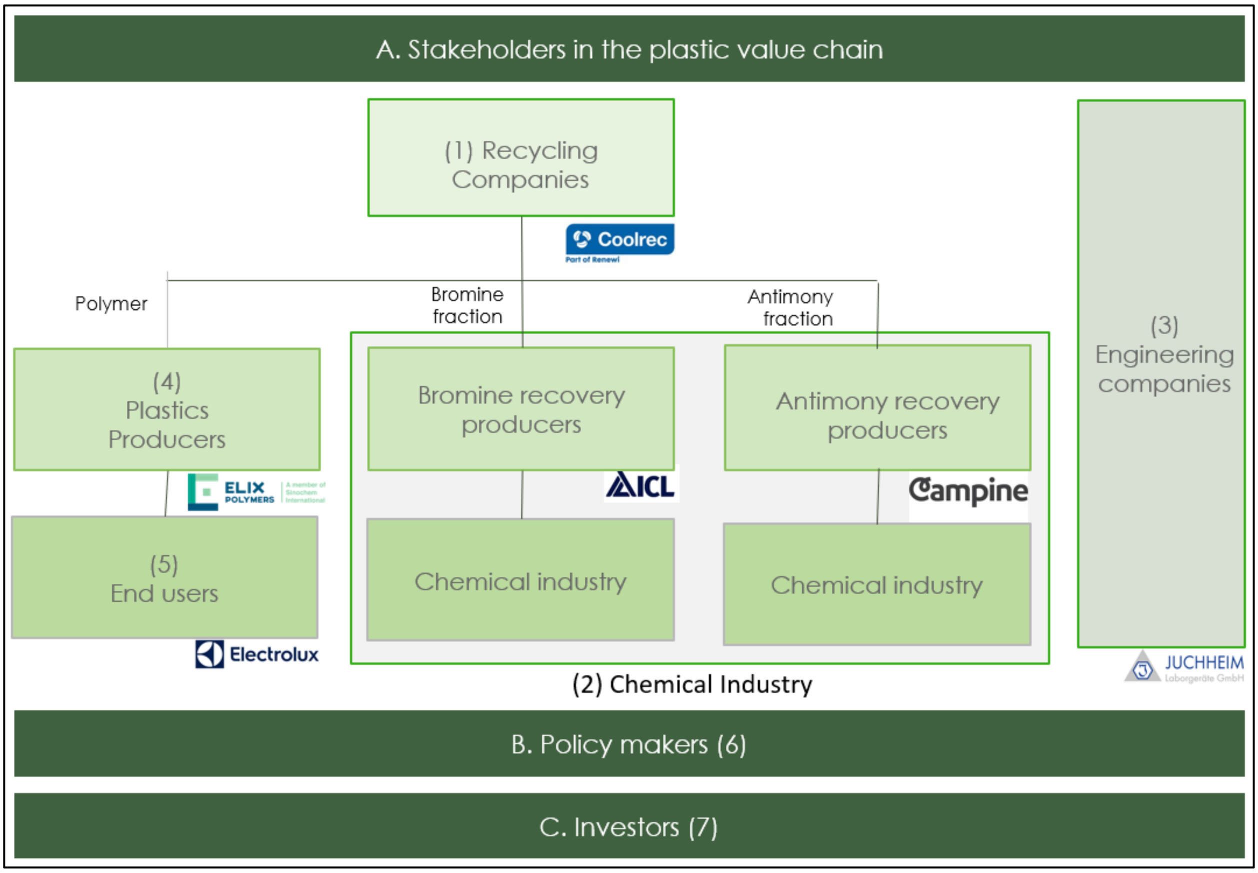

FIGURE 1: TARGET STAKEHOLDERS FOR RECOMMENDATIONS: 1. STAKEHOLDERS IN THE PLASTICS VALUE CHAIN (INCLUDING PARTNERS WITHIN THE PLAST2BCLEANED CONSORTIUM PART OF THE STAKHOLDER GROUP), 2. POLICY MAKERS. C. INVESTORS.

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4. RECOMMENDATIONS

The aim of this report section below is to enhance the market uptake of recycled plastic by providing concrete recommendations and guidelines such as the design of products and standardisation needs. The recommendations were drawn up based on input provided by each project partner from their perspective within the value chain and based on the tasks carried out within the projects. The key recommendations are clustered into the stakeholder groups:

(1) Key recommendations for recycling companies

- **Develop further research to improve sorting as a pre-treatment step to reach industrial targets**: The classification models developed in PLAST2bCLEANED to sort target polymers with Raman spectroscopy are novel, but if used standalone not yet sufficient to reach industrial targets as a pre-treatment step for the recovery of polymer, BFR and ATO. In real waste samples, the sorted target polymers are contaminated with other polymers present in the WEEE stream. Further sorting in combination with other techniques should be studied to reach the target purity requirements as a pre-treatment step for recycling. The WEEE streams that are currently not recycled are a complex mixture of shredded plastics. Future advanced sorting techniques should be applied to improve the sorting as a the first step of the recycling. If further purification is needed, this can be taken up in a next step as part of the recycling process.
- **Achieve DFR through colour of plastic or standard labels:** Due to the technical difficulties of current industrial methods to identify black plastics, it is highly recommended to eco-design EEE and to consider DfR aspects. This can be achieved by choosing the right colorants for plastic components that do not interfere the sorting or by the development of standard labels that allow the identification of this type of waste through optical sorting.
- **Improve plastic type sorting of Polycarbonate (PC)/ABS:** Sorting can be achieved using Near-infrared spectroscopy (NIR), Fourier-transform infrared spectroscopy (FTIR), or RAMAN spectroscopy. The goal for the sorting step is to provide for the PLAST2bCLEANED dissolution process a plastic waste stream consisting of mono-materials as much as possible. With new technological developments at TNO Delft the aspect of colour sorting (black, grey, white, others) can be overcome with an added process step to remove colourants after dissolution. Therefore, the focus of the sorting step should be on improved sorting of plastic type (NIR, FTIR, RAMAN) to arrive at sorted streams containing mono-materials as much as possible.
- **Perform trials with real ABS waste on demo plant level to increase insight in which type of plastics need to be sorted out:** This is the logic next step to test the PLAST2bCLEANED dissolution technology and would help to understand the behaviour if other additional plastics are present even more. This will increase insight into which plastics need to be sorted out as they influence the dissolution or the performance of the recycled materials

(2) Key recommendations for chemical companies:

- **Create more knowledge on DFR and eco-design of EEE.** PLAST2bCLEANED's recommendation is to consider those additives that will not affect the recycling of WEEE plastics.
- **Further improve the BFR and ATO separation and further improve the process steps needed for the dissolution, separation and cleaning**: Based on the obtained results of the BFR

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removal efficiency (around 75%) it is clear that further work is necessary to reach a higher removal efficiency level.
The Bromine fraction recovered at TRL5 contains antimony trioxide and titanium dioxide levels below the analysis threshold of XRF. By appearance it is a black sludge with approximately 37% bromine content (up to 50% BFR content), residual solvent, low molecular weight (Mw) polymer, colourants, and dispersing agents, which should be utilized easily in the ICL Terneuzen recycling plant.
Results of the trials showed that the non-soluble BFRs are still present in the removal side stream alongside the ATO. Therefore, unfortunately, the antimony fraction cannot be utilized at this stage of the project. Although about 60% of Sb was removed via the sediment phase, the fraction is contaminated with insoluble BFR and polymer. More process improvements are necessary. These improvements can be made either in the dissolution process to improve the separation of the polymer from the Sb fraction (e.g., by a decanter) or in the cleaning step of the Sb fraction thereafter to remove the BFRs.

- **Accelerate the technology development for the recovery of bromine and antimony**: For chemical companies, it is recommended to accelerate the technology development of recovery of the bromine and antimony. By recovery of both materials and reuse, the shortage of bromine resources is reduced and less virgin materials needs to be produced, thus reducing the environmental impact. Furthermore, it is recommended to switch to more environmentally and cost-friendly alternatives.

(3) Key recommendations for engineering companies:

- **Support the implementation of advanced sensor-based classification for sorting:** good results were obtained during the TRL5 sorting prototype when validating the operation of the on-line set-up. Advanced Raman sensor-based classification lines could be implemented in the future at pilot scale to increase the sorting even more.
- **Support the creation of a scale-able, cost-efficient and continuous processing plant, complying with ATEX requirements**: For the TRL5 processing plant, dissolution, hot filtration, and spray drying produced good results. The antimony trioxide removal needs to be improved by costly G-force separation methods such as an ATEX decanter centrifuge. This in turn requires a fully continuous setup instead of the current batch-wise processing. Hot filtration and spray drying are run continuously anyways. Therefore, the next scale-up should focus on creating a continuous process. This could be an alternative, continuous, dissolution methodology, or as an intermediate step, the process could be equipped with multiple batch vessels that are each operated intermittently.
  One specific recommendation is on the site where the dissolution plant will be placed. Since the process involves volatile and flammable solvents ATEX requirements apply. Therefore, it would be beneficial if the site for the plant already is used to ATEX type operation and requirements such as a refinery or other chemical operation site.

(4) Key insights for polymer producers:

- **Remove Legacy additives and Br content**: The removal of legacy additives is required in use cases for electronics plastics. This can be provided by the PLAST2bCLEANED process as tests at TRL5 scale showed the feasibility of this process. Clean rABS that passes REACH, POP and SVHC tests can be provided with the process developed with PLAST2bCLEANED. However, remaining Br content in rABS remains above the project goal of <1.000 ppm and

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the removal of Br needs to be further improved. The handling of rABS fibrous powder requires elevated standards of safety.

- **Ensure performance requirements are met for rABS application in products through re-formulation such as the re-additivation of stabilizer and rubber and using a mixture of rABS/vABS**: It was found that mechanical properties of rABS are in line with the ones of vABS. That shows that, except for colour and impact strength properties, the performance of rABS and vABS is similar. However, re-additivation of stabilizers and rubber will be necessary to reach the desired impact strength properties. Also, the project selected a re-formulation in order to achieve the target specs for proposed application.
- **Increase the use of recycled ABS to lower CO_2 footprint**: The LCA assessment has shown that rABS has a lower CO_2 footprint compared to vABS. The costs are unclear yet.

(5) Key insights for end-users:

- **Boost the eco-design of EEE products focusing on DfR through legislation (passing targets) or behavioural change:** End-users could trigger a higher demand of DfR or eco design for EEE products. By changing the EU legislation to provide 30% recycled plastic content in new products, end users might be more aware of the necessity of DfR and ecodesign and they might prefer buying products with an ecodesign/DfR. The project aims for the rABS to pass and be compliant with REACH, POP and SVHC targets. Plast2bCleaned already showed at TRL 5 that washing machine front door parts can be produced from rABS by applying a 70/30 mixture of virgin ABS (vABS)/rABS.
- **Improve decoloration of rABS:** At current state, rABS still contains a grey discolouration. So, currently, the applications are limited to non-visible parts. Reducing the decoloration of recycled ABS (rABS), makes the broader application of rABS in products possible.
- **Create awareness of the real environmental and health impact of recycled material**: LCA and Life Cycle Costing (LCC) comparisons should be made on the basis of virgin vs recycled material within the application to see the real environmental and health impact benefits. The right allocation approach for the emissions and costs should be agreed upon. From a product perspective, recycled ABS would become more attractive if a CO_2 credit would be attached to it.

(6) Key insights for policy makers:

- **Develop instruments such as taxing, regulations, or crediting to account for the CO_2 reductions to make rABS more attractive compared to vABS**: The main question that LCA or LCC can answer in this case is "*What are the impacts of recycling or recovery compared to the state-of-the-art (SoA) waste treatment?*". Through an LCA study it appears that CO_2 emissions are avoided by the PLAST2bCLEANED route of advanced sorting and dissolution of ABS rich waste streams into ABS recyclate. These CO_2 reductions are primarily caused by avoided emissions in avoided production of virgin material. To make these emission reductions valorised and tradeable, an accounting system should be in place allowing for crediting these emission reductions attached to recyclates. The costs of the PLAST2bCLEANED route are not yet clear. In order to stimulate PLAST2bCLEANED waste treatment, additional policy measures should be in place, e.g., a CO_2 tax or regulation. From a product perspective, recycled ABS would become more attractive to end users if a CO_2 credit would be attached to it. Moreover, a good collaboration between all the stakeholders in the value chain should be established to collect the right primary data for analysis. (WP5)

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- **Support the Eco-Design/ DfR by policies to make eco-design without additives more attractive:** The performance tests showed that the performance of rABS is in line with specific grades of vABS. However, the reduced impact strength, will require the companies to use additives to achieve the necessary quality for the final application. DfR could be a possible solution to that. For example, the quality of rABS can be increased through the careful selection of additives in the design of products that have minimal impact on their recycling.
- **Standardise legislation for recycled materials**: Standardise the Registration, evaluation and authorization of chemicals (e.g. REACH, POPs and SVHC tests) of DfR products to lower or remove the barrier to market entry of products that are manufactured with recycled materials.

(6) Key insight for investors:

- **Scale up from the current TRL 5 level to TRL 9 to compare the PLASt2CLEANED route with a business-as-usual, commercial, treatment:** The study estimated the benefits of implementing a novel technology by performing an LCA and an LCC. Those also compared this novel recycling process to an already mature current waste treatment option. Since the recycling technology is still under development and has not reached its commercial stage yet, it is important to scale it up to the same TRL as the current business-as-usual treatment for LCA/LCC assessment. Currently, extrapolation of the results to the scaled-up process presents a lot of uncertainties, and it is heavily dependent on the assumptions and the quality of input data taken. Special care needs to be dedicated to verifying the most important assumptions made about the scaled-up process.

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