Rigid PVC Recycling Workplace Exposure and Environmental Emissions

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Version 1.0

EXCECUTIVE SUMMARY

This report evaluates occupational exposure and environmental emissions associated with rigid PVC recycling operations across four European recycling facilities. The study was commissioned in response to concerns raised by the European Chemicals Agency (ECHA) regarding potential worker exposure to organotin stabilisers and the environmental release of PVC particulates during recycling operations. The assessment was conducted by Plastics Recyclers Europe (PRE) and VinylPlus through on-site exposure monitoring, elemental dust analysis, and review of plant emission data.

The methodology included personal air sampling of workers in representative "worst-case" exposure roles, measuring inhalable and respirable dust in accordance with recognised occupational hygiene standards. Dust samples were further analysed for elemental content including tin (Sn), lead (Pb), cadmium (Cd), antimony (Sn), zinc (Zn), calcium (Ca), and titanium (Ti). Existing plant environmental emission reports and operational risk-management practices were also reviewed to assess broader environmental performance.

The results show that across all monitored facilities, worker exposure to inhalable and respirable dust remained below limits set in this study at 5 mg/m^3 and 1 mg/m^3 respectively based on an overview of National Limit values, indicating general dust exposure is well controlled. Similarly, lead and cadmium exposures remained well below the EU binding occupational exposure limits. Antimony and Zinc, while generally of lesser concern also remained below limits adopted for this report following a review of national limit values. Finally, based on an extreme worst-case calculation assuming all measured tin is caused by a single organotin substance, it can be concluded that there is no unacceptable risk for human health in relation to organotins.

Table 1 Summary of measured airborne concentrations in the breathing zone of 19 workers across 4 EU Recycling facilities and the risk assessment based thereupon.

Substance	Inhalable Dust (mg/m^3)	Respirable Dust (mg/m^3)	Pb (µg/m^3)	Cd (µg/m^3)	Sb (µg/m^3)	Zn (µg/m^3)	Sn (µg/m^3)	Max DOTE (µg/m^3)
Median	0.4	0.09	0.7	0.02	0.03	2.62	0.12	0.8
90th Percentile	1.3	0.15	1.1	0.23	0.27	10.74	0.46	2.9
Reference max exposure level	5	1	30	1	250	500	-	25
RCR	0.26	0.15	0.037	0.230	0.001	0.021	-	0.116

Environmental performance was similarly strong. All participating facilities employed integrated dust extraction and filtration systems that captured airborne particulate emissions as part of the recycling process itself. Measured channelled emissions were extremely low relative to processing throughput, in the range of 0.0007-0.0021%. With regards to the outdoor shredding facilities implemented robust spill-control, housekeeping, sealed storage, rainwater management, and surface-cleaning protocols to minimise diffuse microplastic release. All in all, based on the OECD Emissions Scenario Document for plastics additives and more advanced modelling performed by one of the participating facilities it can be concluded that the total release from shredding is about 0.25% and that most of this (0.2%) is captured by the plants control measures (e.g. street cleaning vehicles), and only 0.01%, 0.01%, and 0.03% are lost to air, soil, and water respectively.

Overall, the report concludes that modern rigid PVC recycling facilities operating under current European best practices present a low occupational and environmental risk profile. Existing engineering controls, ventilation systems, material containment procedures, and operator awareness measures appear highly effective in controlling worker exposure and limiting environmental emissions.

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INTRODUCTION

The European Chemicals Agency's (ECHA) Investigation Report on PVC and its Additives (Appendix A+B, C, D, E, F) raises concerns about 1) worker exposure to organotin substances in PVC recycling facilities, 2) environmental release of PVC particles containing additives from recycling facilities, and 3) worker exposure to plasticisers in flexible PVC recycling facilities (ECHA 2023).

Plastics Recyclers Europe (PRE) and VinylPlus (V+) have agreed on a project to address these concerns. The core idea is to 1) perform workplace exposure measurements for inhalable/respirable dust and subsequent analysis of dust for tin and other elements, 2) collect existing emission measurement data, and 3) perform biomonitoring for plasticiser exposure (flexible PVC only). The outcome of the project will be two reports: this one focussing on findings in rigid PVC recycling and another one focussing on flexible PVC recycling.

METHODS

PLANT SELECTION AND RECRUITMENT

Potential volunteer plants were contacted and provided a two-page briefing describing the project and what would be expected of them. It was expected of the plants to provide currently existing information on workplace exposure, operational conditions and existing risk management measures, and to provide emission measurement reports. Subsequently a virtual meeting was held with plants that expressed an interest to agree on a sampling plan for the plant.

During the virtual meetings, the target was to include 4 workers per plant in the measurement campaign and select the most representative worst case exposure positions. While this may appear to be relatively low number of workers, there were several instances where this proved to be the complete workforce operating the plant per shift. This number of 4 workers was occasionally deviated from in the event that there was a good reason for inclusion of more workers based on the activities performed by the workers.

EXPOSURE MEASUREMENTS

All workers were informed by plant management prior to the execution of the measurement campaign and were explicitly informed that they were under no obligation to participate. Not participating would also not have any negative consequences for their employment.

Qualified PRE Staff travelled to the participating plants to carry out the sampling. The calibrated equipment was rented from RPS Analytics which also carried out the analysis of the collected samples.

Inhalable & Respirable Dust

Each worker included in the study was equipped with two sampling pumps. One fitted with an IOM filter for the collection of inhalable dust, and another fitted with a cyclone filter for respirable dust. These measurements were carried out according to MDHS 14/4 *General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols*.

Elemental Analysis

The following elements in the inhalable dust fraction Sn, Pb, Cd, Ti, Sb, Zn, Ca were quantified by ICP-MS performed according to ISO 30011 *Workplace air — Determination of metals and metalloids in airborne particulate matter by inductively coupled plasma mass spectrometry*.

COLLECTION OF PLANT CONTEXTUAL INFORMATION

PRE Staff collected information on the plants' operational conditions and risk management measures during the visit. Photographs and video were taken during the visit for inclusion in this report. Before inclusion into the report photos were edited in the following ways:

1. Individuals were made unrecognisable in order to protect their identity
2. Identifying markings (e.g. logos) including text in the local language were blurred
3. Any proprietary machinery or processes were cropped or blurred.

Plants were given a period to evaluate the processing and highlight additional aspects that they would not like to have included in the report that would reveal trade secrets.

RISK ASSESSMENT HUMAN HEALTH

Dust

At the moment there is no EU Binding Occupational Exposure Limit (OEL) for dust. However, there is a patchwork of national limit values and practices[1] that places limits on dust exposure in the occupational health and safety sphere. The GESTIS International Limit Value Database was consulted to see what kind of limits have been adopted at national level.

For inhalable dust, several countries (AT, BE, DK, DE (AGS), HU, IE, PL, ES, SE, CH) maintain a time weighted average limit of 10 mg/m^3, while a more limited number of countries (FR, DE (DFG)) maintain a limit of 4 mg/m^3.

For respirable dust, HU has a limit of 6 mg/m^3, AT and US (OSHA) maintains a limit of 5 mg/m^3, IE limits exposure to 4 mg/m^3, BE, ES, and CH set the limit at 3 mg/m^3, DE has a limit of 1.25 mg/m^3 (AGS) and a limit of 0.3 mg/m^3 (DFG), and finally FR has a 0.9 mg/m^3 limit.

For the purpose of this report a level of 5 mg/m^3 for inhalable dust and a level of 1 mg/m^3 for respirable dust will be considered safe. This is somewhat an arbitrary choice roughly based on the lower side of the spectrum of what Member States have adopted.

Lead and Cadmium

There are EU Binding Occupational Exposure Limit values for lead and cadmium in the Carcinogens, Mutagens and Reprotoxic substances Directive (CMRD), which are 30 and 1 $\mu g/m^3$, respectively. These are considered appropriate for this report and airborne concentrations of these elements will be compared with these limit values.

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[1] For example, NL does not have a limit value on dust, but does maintain that in a workplace risk assessment employers must for those substances without a national limit look abroad to find a limit value.

Organotins

ECHA in its investigation report indicated that 10 organotin substances were possible to be used as heat stabilisers in PVC; of which 5 or 6 may be in use in the EU (Table 2, with presumably used substances in bold).

In reality, due to the production process of organotins, it is not normally the case that commercial substances are purely one or the other molecule (Graf 2000). For example, DOTE is produced by first reacting tin tetrachloride and certain organometallic compounds to produce tetraoctyltin. Tetraoctyltin can then be reacted with an equal part tin tetrachloride to produce **mainly** dioctyltin dichloride, with an impurity of monooctyltin trichloride and trioctyltin chloride. This isomeric mixture is then reacted with isooctyl mercaptoacetate to produce **mainly** dioctyltin bis(2-ethylhexyl thioglycolate), with some monooctyltin tris(2-ethylhexyl thioglycolate) (MOTE) and trioctyltin 2-ethylhexyl thioglycolate.

Given the adverse properties of DOTE, years ago a switch has been made to MOTE. Unfortunately, while the chemical reaction to produce trioctyltin chloride and dioctyltin dichloride from tetraoxtyltin and tin tetrachloride proceeds smoothly, the production of monooctyltin trichloride is more challenging and results in somewhat more substantial impurity of dioctyltin dichloride. As such in the subsequent step with isooctyl mercaptoacetate, DOTE becomes a substantial impurity in MOTE. A serious effort has been made over the past years that has resulted in the possibility of to supply MOTE with ever lesser concentrations of DOTE.

For those substances with human health hazard classifications (DOTE, DMTE, and MMTE) ECHA performed a quantitative risk assessment comparing exposure highly conservative exposure modelling results with Derived No Effect Levels (DNELs) for these substances.

The quantification of DOTE, DMTE, and MMTE in inhalable/respirable dust is difficult[2] and considerably more laborious and thus expensive than the quantification of the elemental tin content. Furthermore, while it is possible to first weigh the inhalable fraction and subsequently analyse it with ICP-MS to determine the elemental composition, it is not possible to weigh the inhalable fraction **and** perform ICP-MS **and** quantify DOTE, DMTE, and MMTE. Direct analysis of these substances would require an additional pump and sample on the worker that is already having to tolerate the presence of two such pieces of equipment.

A more efficient approach would be to calculate extreme worst case concentrations of DOTE, DMTE and MMTE, assuming that all airborne tin is caused by a single one of these substances. For example, if 1 µg/m^3 of tin is measured in the breathing zone of a worker in a recycling facility and it is assumed that this 1 µg/m^3 is caused fully by DOTE with a tin content of 15.8% then the worst-case maximum concentration of DOTE is 1 [µg Sn/m^3] / 0.158 [Sn/DOTE] = 6.3 µg DOTE/m^3.

If these extreme worst-case maximum concentrations are below the limit values for these substances, then the worker is operating safely. If the worst-case maximum concentrations exceeds the limit value, it is not proof that the worker is operating in concentrations above the limit value, but would require further follow-up specific measurements to determine the exact concentration of the substance in question. In the example above the DNEL for worker inhalation exposure is 25 µg DOTE/m^3 and it can be concluded that the worker is operating safely.

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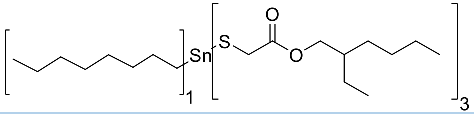
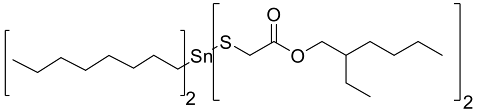
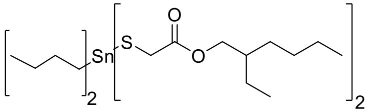
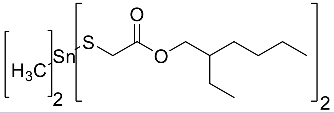
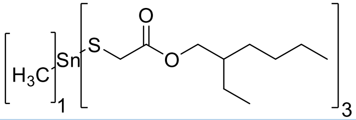
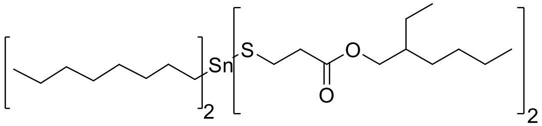
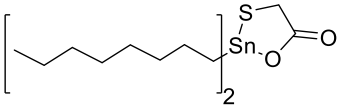
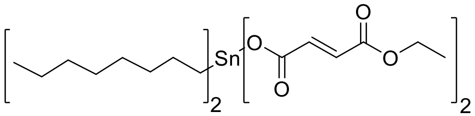
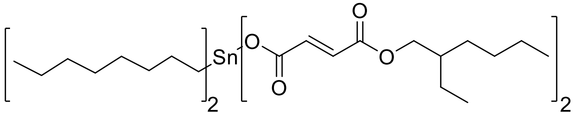
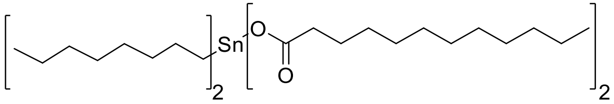
[2] Typically, the direct carbon-Sn bond is very much covalent, while the O-Sn or S-Sn is somewhat ionic. When these kinds of molecules are used in polymers, the carbon-Sn bond maintains cohesion while the O-Sn bonds may dissociate resulting in an organotin ion such as dibutyltin^{2+} and an anion such as in this example two dodecanoate CH3–[CH2]$_{10}$–COO^{1-}. One would have to quantify the organotin ion and the anions within the material separately and make assumptions on their association.

The ECHA PVC Investigation Report indicates that a limit value of 25, 180, and 5750 µg/m^3 are applicable to DOTE, DMTE, and MMTE. These limit values will be used to evaluate the maximum DOTE, DMTE, and MMTE concentrations to calculate maximum RCRs for risk assessment.

The conservativeness of this approach should not be underestimated. In Europe around 8600 tons of organotins are used, with the majority of this (5900 tons) in short life cycle applications such as packaging (films). The remaining volume is used in building and construction (B&C), automotive, and medical applications (blister packs). The use of organotins in construction profiles was/is a practice that is mainly restricted to the US, while in the EU cadmium, then lead, and now calcium/zinc stabilisers are used. The use of DOTE itself has been largely phased out in the EU over the past years and the impurity of DOTE in MOTE has seen a decline over the same period as well. Furthermore, what little organotin was used in B&C was mainly methyltin- rather than octyltin-based. As such RCRs calculated based on the maximum airborne DOTE concentration will be result in a large overestimation of risk.

Table 2 Structures, name, abbreviation, EC/CAS number, registered tonnage, and uses of organotin molecules.

Structure	Name	Abbreviation	EC / CAS	Aggregated Tonnage (active registrants)	
	**Monooctyltin bis(2-ethylhexyl thioglycolate)**	**MOTE**	**248-227-6 27107-89-7**	**1000-10000 (4)**	**Pipe fittings, Packaging (food and non-food), Automotive parts, Medical packaging (blister packs)**
	**Dioctyltin (2-ethylhexyl thioglycolate)**	**DOTE**	**239-622-4 15571-58-1**	**1000-10000 (5)**	**Pipe fittings, Packaging (food and non-food), Automotive parts, Medical packaging (blister packs)**
	Dibutyltin bis(2-ethylhexyl thioglycolate)	DBTE	234-186-1 10584-98-2	10-100 (4)	No identified uses
	**Dimethyl bis(2-ethylhexyl thioglycolate)**	**DMTE**	**260-829-0 57583-35-4**	**1000-10000 (4)**	**Pipe fittings, Packaging (food and non-food), Automotive parts, Medical packaging (blister packs)**
	**Monomethyl tris(2-ethylhexyl thioglycolate)**	**MMTE**	**260-828-5 57583-34-3**	**1000-10000 (12)**	**Pipe fittings, Packaging (food and non-food), Automotive parts, Medical packaging (blister packs)**
	**Dioctyltin bis(2-ethylhexyl mercaptopropionate)**	**DOT-MalEt**	**261-645-3 59185-95-4**	**10-100 (1)**	**No identified uses**
	**2,2-dioctyl-1,3,2-Oxathiastannolan-5-one**	**DOTTG**	**239-581-2 15535-79-2**	**Ceased Manufacture**	**Pipe fittings**
	Dioctyltin bis(ethyl maleate)		268-500-3 68109-88-6	100-1000 (3)	Pipe fittings
	Dioctyltin bis(ethylhexyl maleate)		233-117-2 10039-33-5	10-100 (2)	No identified uses
	Dioctyltin dilaurate	DODL	222-883-3 3648-18-8	100-1000 (6)	No identified uses

Antimony, Calcium, Zinc, and Titanium

Antimony trioxide if added to PVC formulations would potentiate the inherent flame retardancy of the PVC material (Schiller 2015; Weil and Levchik 2009). This is normally not needed and thus not done in rigid PVC formulations. However, in flexible PVC formulations, where the addition of plasticiser reduces the flame retardancy of the material, antimony trioxide may be used. As the marginal cost of inclusion of antimony under the ICP-MS method was zero, it was decided to quantify antimony in inhalable dust also for rigid PVC.

The GESTIS International Limit Database reveals that only Finland adopted a limit value specific to Antimony dioxide of 0.5 mg/m^3. Two European countries adopted a limit value for “Antimony and compounds, except antimony trisulphide, antimony trioxide and antimony hydride”: AT and NL at 0.5 mg/m^3. Finally, 16 countries have set a limit for “Antimony and its Antimony compounds (except stibine)” as Sb at: 0.5 mg/m^3 in AT, BE, DK, FI, FR, HU, IE, NO, PL, ES, CH, NL, and UK; 0.25 mg/m^3 in SE; 0.2 mg/m^3 in LV and RO. For the purpose of this report, it is assumed that a limit of 0.25 mg Sb/m^3 would be protective of human health.

Calcium in PVC formulations can be present because of two different types of additives used: calcium(-zinc) stabiliser packs and calcium carbonate (Schiller 2015). Calcium carbonate (i.e. limestone) is a filler additive used in a wide variety of plastics (and other materials). The GESTIS International Limit Database, reveals that limits have been adopted for calcium carbonate in 7 European countries: 10 mg/m^3 in FR, HU, IE (inhalable fraction), PL, and UK (inhalable fraction); 6 mg/m^3 in LV; 4 mg/m^3 in IE (respirable fraction) and UK (respirable fraction), and 3 mg/m^3 in CH. Given the similarity of these limits with the general dust limits, it seems that these limits for calcium carbonate might be set to control dust exposure and not because of inherent toxicological properties of the substance. Next to this Calcium stabilisers tend to be calcium fatty acid salts which are not of any toxicological relevance. As such, no quantitative risk assessment for calcium exposure is performed.

Zinc exposure can be due to the use of zinc stabilisers or zinc oxide in PVC (Schwab et al. 2015; Schiller 2015). Zinc oxide is a UV stabiliser additive used in thermoplastics and zinc stabilisers are normally zinc fatty acid salts used in PVC formulations exclusively. However, the main use of zinc oxide, in general, is in the rubber industry where it plays a role in the vulcanisation process and exposure to zinc in the mechanical processing of PVC wastes containing rubber may contribute to zinc exposure.

The GESTIS International Limit Database indicates that there are limits in several European countries for either: “Zinc oxide, dust”, “Zinc oxide”, or “Zinc and its compounds, inorganic, inhalable aerosol” set at: 10 mg/m^3 in FR, NO (inhalable), and ES; 5 mg/m^3 in HU, NO (respirable), PL, and SE; 3 mg/m^3 in CH, 2 mg/m^3 in BE (respirable), FI, DE (DFG); and 0.5 mg/m^3 in LV. Again, similar to, but perhaps slightly lower than, for regular dust. For the purpose of this report, it is assumed a limit of 0.5 mg Zn/m^3 is protective of human health.

Finally, titanium is an indicator of the presence of titanium dioxide (Auer et al. 2017; Schiller 2015). Titanium dioxide reflects electromagnetic radiation that has roughly double the wavelength of size of the particles. As such TiO2 particles with a size of 190 – 390 nm reflect visible light and pigmentary TiO2 tends to have a particle size distribution that is designed to match. There are also grades of nano-TiO2, with much smaller particle size distributions, however this is primarily used in sunscreens to protect against UV radiation (which has a smaller wavelength than visible light). In PVC formulations only pigmentary TiO2 has been used and while such pigmentary TiO2 will have a particle size distribution that has a tail extending in the sub 100 nm range, this is but a very small fraction of the pigmentary grade. As such specific recommendations regarding the nanoform of titanium dioxide such as the limit of 0.8 μg/m^3 proposed by ANSES do not apply here (ANSES 2020).

The GESTIS International Limit Database states that there are limits in European Countries for “Titanium dioxide”: 11 mg/m^3 in FR; 10 mg/m^3 in BE, IE (inhalable), LV, PL, RO, ES, and UK (inhalable); 6 mg/m^3 in DK; 5

mg/m^3 in AT (respirable), NO, and SE; 4 mg/m^3 in IE (respirable) and UK (respirable); and 3 mg/m^3 in CH (respirable). Germany (DFG) has a limit of 0.3 mg/m^3 for the respirable fraction, that must be multiplied by the material density. In general, the toxicity of TiO2 does not seem to be very much related to the substance, but rather to the particulate nature of the material (RAC 2017; Heinrich et al. 1995). As such, any risk is covered by the risk assessment for dust and no specific risk assessments for titanium dioxide exposure is performed.

For antimony and zinc there will be a risk characterisation included in the plant reports. The data for calcium and titanium will however be available along with all other raw data in the annex I.

Note on respiratory protective equipment

When respiratory protective equipment is used during certain measurements, this has a consequence on the exposure of the worker. There are two potential ways to take this into consideration in industrial hygiene. It is possible with certain pieces of respiratory equipment to modify these to measure the airborne concentration inside of the mask. This is however rarely done since one has to make a custom modification to the RPE (e.g. drill a hole in the mask, fit it with a valved sampling port) which tends to render the RPE unsuitable for normal use (e.g. having a sampling port on the mask means that it increases the leak chance when not sampling).

An alternative approach is to measure the airborne concentration as usual in the breathing zone of the worker and then to use a “protection factor” to calculate the exposure of the worker. There are nominal protection factors (NPF) which are derived based on the assumption that filters are perfectly efficient and using the leak through rate of the mask. For example, a powered respirator according to EN 12942 TM3 level has a maximum leak through rate of 0.05% and thus a nominal protection factor of 2000. In several countries, committees of industrial hygienists and other experts have evaluated various different types of RPE and established “assigned protection factors” (APF), which take into account imperfection of equipment, user behaviour and are to varying degrees conservative (see Table 3 for an overview of dusk mask factors).

In the present study the use of dusk masks was observed. Depending on the filter type used, such masks reduce exposure by a nominal factor of 4 – 48, though assigned protection factors range from 4 – 30 (see Table 3). For this report a protection factor of 10 is assumed for risk characterisation, since P1 type filters are a rarity and normally filters used on reusable half mask filters are either P2 or P3.

Table 3 Nominal and assigned protection factors of a selection of respirators for dust exposure management. Based on (INRS 2019; EN 529:2005 Respiratory protective devices - Recommendations for selection, use, care and maintenance - Guidance document ; SELECTIE EN GEBRUIK VAN ADEMHALINGSBESCHERMINGSMIDDELEN 2001). NPF means Nominal Protection Factor. For an extensive discussion on respiratory protective equipment and nominal vs assigned protection factors see EUROPUR Safety Guidelines section D3.1 (Safety Guidelines for the Flexible Polyurethane Foam Industry 2023)

Standard	Description	Class	NPF	FI	DE	IT	SE	GB	NL	FR
EN 149	Disposable half mask respirator	FFP1	4	4	4	4	4	4	4	
		FFP2	12	10	10	10	10	10	10	
		FFP3	50	20	30	30	20	20	20	10
EN 140	Reusable half mask respirators	P1	4	4	4	4	4	4	4	
		P2	12	10	10	10	10	10	10	
		P3	48		30	30		20	20	10
		Gas	50	20	30	30	30	10	10	

ENVIRONMENTAL EMISSIONS

Channelled emissions

All plants provided emission measurement reports in which their channelled emissions to air were quantified. These were provided to PRE and will be summarised below. Furthermore, plants reported they had no process wastewater emissions as they either did not use water in their process or had the facilities to process their process water in such a way that allowed reuse. This processing did generate sludge which was directed towards disposal.

Diffuse emissions

All plants were aware of the potential for diffuse emissions (e.g. spillages) and had put measures in place to address these.

PLANT REPORTS

PLANT A

Plant A is a plant treating several tens of thousands of tons of construction profile waste per year receiving these profiles from both pre- and post-consumer origin. A rough plant outline can be found in Figure 1.

Figure 1 Plant A Layout. Blue is outdoor area for receiving of profile waste; green is indoor building where mechanical processes occur; yellow is indoor building where regrind is extruded with melt filtration to produce pellets; sealed big bags of finished product is stored in an outdoor area (purple). Office buildings not shown.

The received material is stored on an impermeable surface with rainwater runoff capturing system (see Figure 2).

Figure 2 Stored construction profile waste. Left: predominantly post-consumer material. Right: more pre-consumer material.

The rough construction profile waste contains PVC and non-PVC materials inherent to their construction or collection such as: steel or aluminium reinforcements, glass, rubber, wood, and other polymers (e.g. PMMA). In a first processing step this material is fed into a shredder (Figure 3).

Figure 3 Line Input Operator feeding outdoor shredder. Left: collection of profile waste. Right: feeding the first shredder.

From the shredding unit the shredded material is conveyed to a large industrial sieve to ensure that only material with a certain maximum size continues forward into the plant for further processing. Material with a larger size is collected in a large container and will be reintroduced into the first outdoor shredder once such material has been collected in sufficient quantity.

This mixed shredded material stream is subsequently subjected to dust extraction the air stream carrying this dusty and fluff material is directed towards the site's air extraction and cleaning systems (Figure 4). The dust but also fluff material (e.g. EPS foams that can be present in the waste) is captured by this air cleaning system and drops into a big bag which is directed towards final disposal.

The dedusting of the material stream also occurs at other points throughout the process and all the resulting air stream is treated in a similar way. A proportion of the captured dust will be microplastics. This proportion will increase throughout the process since the initial dedusting steps are done on the rough material that will contain all sorts of (non-targeted) non-PVC materials, and the process progressively remove the non-PVC materials. As such, the vast majority of dusty microplastics will be captured by exhaust ventilation, removed from the air stream, and carefully directed towards final disposal again, limiting environmental release of these particles.

Following the initial dedusting, the material is shredded for a second time before the first separation step which removes ferrous metals (i.e. steel) by magnetic separation and eddy current separation to remove non-ferrous metals (predominantly aluminium). These ferrous and non-ferrous metal fractions are directed towards the metals recycling industry and provide a minor source of revenue for PVC recyclers.

Figure 4 Left: Air Extraction Cleaning System with particulate filters. Right: Captured particulate matter.

The remaining material stream contains predominantly PVC, but also rubber, wood and other contaminants. The shredding step will have resulted in the different materials obtaining varying and sometimes overlapping size distributions; residual glass shatters to tiny pieces, PVC breaks to defined sizes, and rubbers tend to be less affected and be present in somewhat larger pieces. Through sieving, a first product fraction of a "B-Grade" PVC is obtained which is used in lower end construction profiles, a main material stream for further processing, and another waste fraction of larger rubber pieces is produced. This "rubber" fraction consists of various rubber-like materials used in profile systems (e.g., EPDM, flexible PVC, SBR, and natural rubber) and is sent for disposal.

The main material stream is treated with a combination of sorting technologies including density sorting. The latter removes any low-density material such as wood (Figure 5 left), which is directed to disposal. The remaining higher density material stream is subsequently subjected to grinding to further reduce the size of the material.

Figure 5 Left: Waste output of the density separation step. Right: Construction profile regrind before final mechanical processing in plant A.

Following the grinding process, a sorting step to remove more rubber and glass is performed, and the main materials stream is moved into a silo, which acts as a buffer for the final mechanical processing. At this point, the main material stream (see Figure 5 right) contains white, grey, and coloured rigid PVC as well as black and coloured rubber.

Final mechanical sorting is done by a combination of sieving, colour sorting, and electrostatic sorting to produce:

1. Rubber Waste Fraction
2. B-grade PVC Regrind
3. Coloured PVC Regrind
4. Gray PVC Regrind
5. White-grey PVC Regrind
6. White PVC Regrind

All except the B-grade PVC regrind are processed by either extrusion with melt filtration or micronization. The vast majority of the volume is composed of coloured, grey, white-grey, and white PVC regrinds and these are treated in extrusion with melt filtration. Only a minute part of this volume is micronized for specific customers that desire micronized input materials.

Extrusion with melt filtration is a process whereby the PVC material is molten in an extruder, and the molten PVC material is passed over a fine mesh metal sieve. This final step will remove the minute amount of final residual non-melting parts from the material. The equipment measures the backpressure that this metal sieve causes to the molten material stream, which gradually increases as it gets clogged with non-melting parts. Periodically, the metal sieve needs to be replaced by an operator, which then also results in a "filter cake", which is PVC material that is directly on top of the sieve and removed manually. Figure 6 shows such a machine in operation and an example of such a filter cake once it has cooled down showing the types of impurities that are removed by melt filtration which includes: residual metal, wood, rubber, and other polymers (which melt at higher temperatures).

The process of extrusion with melt filtration also normally allows a degree of compounding, i.e. adding new additives to the material. The degree of compounding in plant A is rather limited and mainly involves the addition of colour batch in certain grades of output.

Figure 6 Left: Extruder equipped with melt filtration, Right: Typical filter cake showing impurities captured on a metal sieve during melt filtration.

The hot pellets that result from this process are transported pneumatically by air in tubing towards a cooling tower. On the cooling tower the material slowly, under agitation, drops down a spiral under a gentle air current cooling the pellets before being poured into a big bag. The big bags are sealed and brought to a storage area ready for shipment to customers in the plastics converting industry.

Finally, there is a laboratory quality control operation within the plant. In this lab, an operator takes samples of recycled PVC and prepares things like tensile strength bars with them for determining physical mechanical properties of the produced material.

Figure 7 Laboratory Quality Control Operations

Risk Assessment for Human Health

There are 5 - 7 workers normally operating the plant:

- 1 – 2 Outdoor shredder operators
- 1 (– 2) Indoor mechanical sorting operators
- 2 – 3 Extrusion line operators
- 1 Laboratory/maintenance operator

The outdoor shredder operators spend the majority of their time on outdoor heavy equipment, primarily wheel loaders, to feed the outdoor shredder. They also have a more minor role in the assistance of truck drivers coming to unload waste material onto the plot, where they offer directions and take pictures of the delivered material for quality control of the input material.

The indoor mechanical sorting operator normally works alone, however on the day of the measurement campaign a trainee was shadowing the operator to learn how to perform the job. The job involves unloading of big bags at dedicated facilities, operating a forklift truck to empty containers in the plant that capture the various waste outputs of the plant, keeping track of whether equipment is performing as it should, reporting and/or correcting any deviations.

Extrusion line operators are primarily performing the melt filtration filter replacements and other more minor operation on the extrusion lines. A secondary role is the removal and sealing of big bags when filled with recycled product and operating the forklift to transport these sealed and filled big bags to the storage area.

The laboratory/maintenance operator performs maintenance on plant equipment and collects samples from the different steps in the process for quality control. The operations in the lab consume the most of his time and are mainly on sample preparation and the testing of physical mechanical properties of the materials produced. On the day of the measurement, the operator spent a part of his time in the mechanical sorting department on maintenance activities.

4 workers were included in the exposure measurement campaign: 1 outdoor shredder operator, 1 indoor mechanical sorting operator, 1 extrusion line operator, and 1 laboratory/maintenance operator.

Dust

Dust measurements performed in Plant A revealed that all workers were exposed to respirable and inhalable dust below the limit values adopted for this report of 1 and 5 mg/m^3 for respirable and inhalable dust respectively (see Table 4 for results and Table 32 for raw measurement data). As such there is no adverse effect expected from exposure to dust.

Table 4 Results of the respirable and inhalable dust measurements in Plant A and Risk Characterisation Ratios (RCR) based on a limit of 1 mg/m^3 for respirable and 5 mg/m^3 for inhalable dust. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Respirable (mg/m^3)	RCR	Inhalable (mg/m^3)	RCR
A1	JJ - Outdoor shredder operator	161	<0.14	<0.14	0.43	0.09
A2	TM - Mechanical sorting operator	180	0.13	0.13	1.00	0.20
A3	SK - Extrusion Operator	205	<0.11	<0.11	0.46	0.09
A4	FP - Lab Technician	203	0.18	0.18	0.42	0.08

The highest inhalable dust concentration was found in the mechanical sorting operator, which makes sense as the outdoor shredder operator is operating for the majority of its time in a cabin of a heavy vehicle, the extrusion process is not very dusty, and the few dusty operations in the lab (e.g. CNC equipment) are performed in enclosed systems.

Lead and Cadmium

Cadmium and lead measurements in Plant A reveal concentrations well below their occupational exposure limits in the CMRD (see Table 5 for results and Table 32 for raw measurement data).

Table 5 Results of the cadmium and lead in inhalable dust measurements in Plant A and Risk Characterisation Ratios (RCR) based on a limit of 1 µg/m^3 for cadmium and 30 µg/m^3 for lead. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Pb (µg/m^3)	RCR	Cd (µg/m^3)	RCR
A1	JJ - Line Input Operator	161	0.683	0.023	<0.016	<0.02
A2	TM - Sorting Line Operator	180	1.750	0.058	0.028	0.03
A3	SK - Extrusion Operator	205	0.129	0.004	<0.012	<0.01
A4	FP - Lab Technician	203	0.516	0.017	<0.012	<0.01

Organotin

No tin was detected in the inhalable dust fraction of plant A. As such all concentrations are calculated based on the limit of detection of the analytical method which was 50 ng/sample, which translates into various limits of detection for tin (range 0.12 – 0.16 µg/m^3) dependent on the sampled air volume (see Table 32 for results and Table 32 for raw measurement data). The limit of detection was sufficiently low to conclude that the maximum RCRs are sufficiently below 1, indicating that workers in plant A are not at risk from organotin exposure.

Table 6 Results of the tin in inhalable dust measurements and calculation of maximum organotin concentrations in Plant A and Risk Characterisation Ratios (RCR) based on a limit of 25, 180, and 5750 µg/m³ for DOTE, DMTE, and MMTE. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sn (µg/m³)	Max DOTE (µg/m³)	Max DMTE (µg/m³)	Max MMTE (µg/m³)	Max DOTE RCR	Max DMTE RCR	Max MMTE RCR
A1	JJ - Line Input Operator	<0.16	<0.98	<0.73	<0.97	<0.04	<0.004	<0.0002
A2	TM - Sorting Line Operator	<0.14	<0.88	<0.65	<0.87	<0.04	<0.004	<0.0002
A3	SK - Extrusion Operator	<0.12	<0.77	<0.57	<0.76	<0.03	<0.003	<0.0001
A4	FP - Lab Technician	<0.12	<0.78	<0.57	<0.77	<0.03	<0.003	<0.0001

Antimony and zinc

Traces of antimony were detected in the dust at levels far below the 250 µg Sb/m³ limit. Zinc was found at slightly higher concentrations but still well below the 500 µg Zn/m³ limit. No adverse impact on human health is to be expected from antimony or zinc exposure.

Table 7 Results of the antimony and zinc in inhalable dust measurements in Plant A and Risk Characterisation Ratios (RCR) based on a limit of 250 µg/m³ for antimony and 500 µg/m³ for zinc. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Sb (µg/m³)	RCR	Zn (µg/m³)	RCR
A1	JJ - Line Input Operator	161	0.043	0.00017	9.63	0.019
A2	TM - Sorting Line Operator	180	0.111	0.00044	11.94	0.024
A3	SK - Extrusion Operator	205	0.341	0.00137	3.66	0.007
A4	FP - Lab Technician	203	0.295	0.00118	7.13	0.014

Environmental Emissions

Channelled Emissions

As described in the plant description section of this chapter, the plant is equipped with extensive air/dust extraction systems throughout the mechanical treatment part of the plant. In fact, the removal of dust is an integral part of the recycling process. The air streams thus collected are led to air extraction cleaning systems where the contaminant dust and light material is collected into big bags (see Figure 4). The facility is equipped with 4 air extraction and cleaning systems which collectively extract 91500 m³ of air per hour from various point in the production process. The total dust emission post filtering is 42.5 grams per hour, while the facility processes roughly –3 – 4 tons per hour (Data per stack can be found in Table 8). This means that the process channelled emission factor is 0.0011 – 0.0014%. Only a fraction of this release rate is actually PVC or plastics, since the input material is also containing other materials such as wood, minerals (e.g. sand), metals and more. As such, the release of microplastics from plant A strictly limited.

Table 8 Results of channelled emission measurements in plant A

Parameter \ Stack	Mechanical Treatment 1	Mechanical Treatment 2	Mechanical Treatment 3	Extrusion Department
Flow rate (m/s)	12.3	15.1	12.4	11.2
Flow rate (m^3/h)	26400	31200	25800	8100
Total Dust (mg/m^3)	0.44	0.27	0.77	0.022
Total Dust (kg/h)	0.012	0.0085	0.020	0.0018
Total Dust (g/h)	12	8.5	20	1.8

Diffuse Emissions

Next to channelled emissions, there is also potential for diffuse emissions. While difficult to impossible to quantify these, the plant has put several measures in place with an aim of minimising the environmental release.

The site has an impermeable surface for the storage of waste with rainwater runoff collection system. The rainwater passes a filter before discharge into the sewage system. A measurement was performed on the emitted rainwater in which 15.9 mg/l suspended solids were measured. A fraction of which might be microplastics. However, quantification of annual release of microplastics from rainwater would be a massive scientific endeavour and require a very large number of samples taken over a long period with varying weather conditions and various levels of waste stocks on the premise. While scientifically interesting, it would also be exceptionally costly; the local inspectorate deemed the single measurement, revealing that the suspended solids were low, sufficient for its purposes.

One of the reasons why these emissions are low is because plant A has measures in place to prevent the entry of material into the rainwater runoff. For example, periodically forklift operating sweeping equipment pushes any spread microplastics back to the piles of profile waste (see Figure 8 left) ensuring that plastic particles do not spread beyond their designated storage areas. Specialised cleaning equipment was also available for spillages (see Figure 8 right) and operators received instruction on how to use as was observed during the site visit (see Box 1). A street cleaning vehicle is used daily to collect any microplastics that may have strayed from the dedicated waste storage areas to surrounding drivable areas.

Figure 8 Cleaning equipment used to control spread of microplastics on site. Left: forklift mountable brushes. Right: broom and mechanical sweeping and collection equipment.

Box 1 Eyewitness report of plastics spillage

On the day of the measurement, a truck carrying big bags with regrind arrived. These were destined to be introduced into one of the intermediate silos in the mechanical treatment department having been pre-processed by another firm. The big bags were however loaded onto rather poor quality flimsy wood pallets and sometimes were not placed straight onto the pallets. Despite this, the forklift operator unloading these pallets managed to safely and effectively remove almost all big bags from the truck (sometimes actually managing to wiggle the big bags more straight onto the pallets!). Unfortunately, halfway through the unloading procedure, while removing the pallet, the pallet broke, and the big bag dropped 1.5 meters in height onto the surface of the unloading site. Plastic regrinds spilled from the side of the bag onto the impenetrable surface.

The forklift truck operator and driver remained calm, and radioed for reinforcements. His colleagues arriving rapidly assessed the situation and a large metal open top container was organised (opening of 1.5x1.5 m and a height of approximately 1.2 m). The forklift truck driver and his colleagues carefully mounted the big bag by the top straps onto the forks of the forklift and the forklift operator in a rapid succession of movements maneuverer the spilling big bag over the large container ensuring that most of the regrind in the bag would be collected in the container.

Following the complementary shovelling work, brooms were used to collect the more finely dispersed material into the large container. Whereafter only a very limited amount, was left on the asphalt.

Following this the remaining big bags were unloaded and after the truck left the street cleaning car was used to collect the remaining material for disposal. The regrind collected into the large container was recycled. Also, the plant management was informed and sent a complaint to the supplier about the flimsy wood pallets used for the delivery.

All in all, there tends to be good awareness amongst the plant operators of the importance of limiting microplastics release and considerable efforts are maintained to minimise the release of microplastics from the site.

PLANT B

Plant B treats between 50 and 70 Kt of construction profile waste annually. A plant layout is provided in Figure 9.

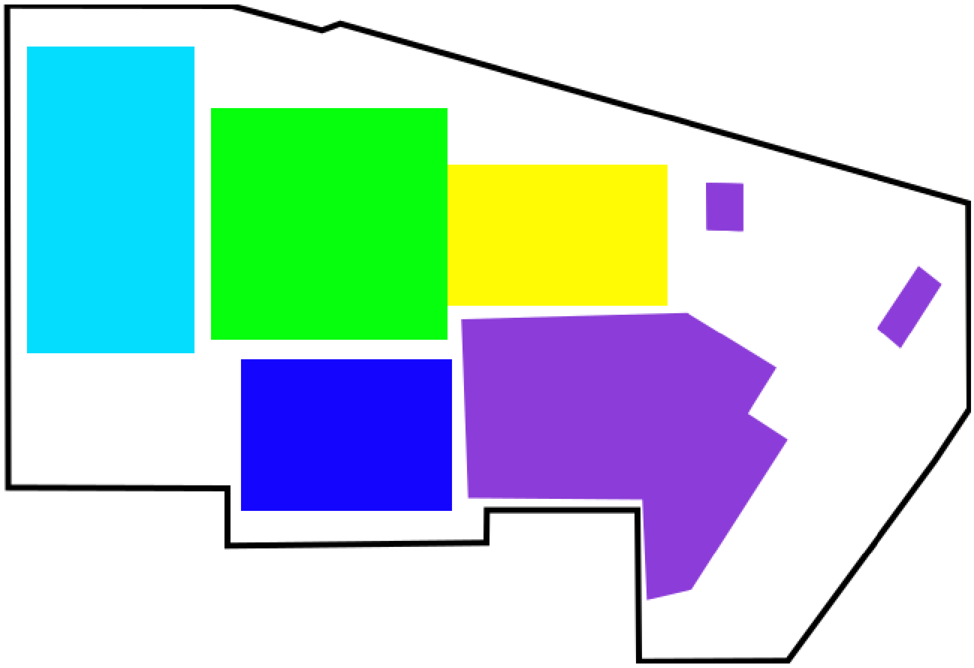


Figure 9 Plant B Plant Layout. Highlighted areas are: storage of pre-consumer profile waste (light blue), storage and receipt of post-consumer profile waste (dark blue), hall with mechanical sorting operations (green) and extrusion department and finished product storage (yellow).

The pre-consumer material is received mainly in specifically designed transportation containers. For example, a metal crate system is provided to profile houses for the collection of off-cuts (see Figure 10), while discontinued profiles are received in specific rack systems. A smaller volume of pre-consumer material arrives in more bulk form. Post-consumer waste material is received in bulk tipping trucks which deposit in an outdoor area near the outdoor shredder.

Figure 10 Stored construction profile waste plant B. Left: predominantly post-consumer material ready for outdoor shredding operation. Right: crate system of the collection of off-cuts from profile houses

Both pre- and post-consumer profile waste will contain non-PVC materials such as steel and/or aluminium reinforcements, rubber, wood, and other polymers that are used in the construction of profiles. Post-consumer waste will in addition contain glass and mineral contamination. Plant B has separate lines to perform initial processing of pre-consumer profiles and post-consumer profiles, as the processing approaches vary.

Processing of pre-consumer profiles is mainly a first shredding to reduce the size to a degree that allows for manual sorting, with off-cuts directly fed into the line. The manual sorting is performed to remove certain specific impurities that can be misplaced by profile houses into the collection system (Figure 9). Following this step, the material is grinded and moved to silos for further processing in the electrostatic sorting hall.

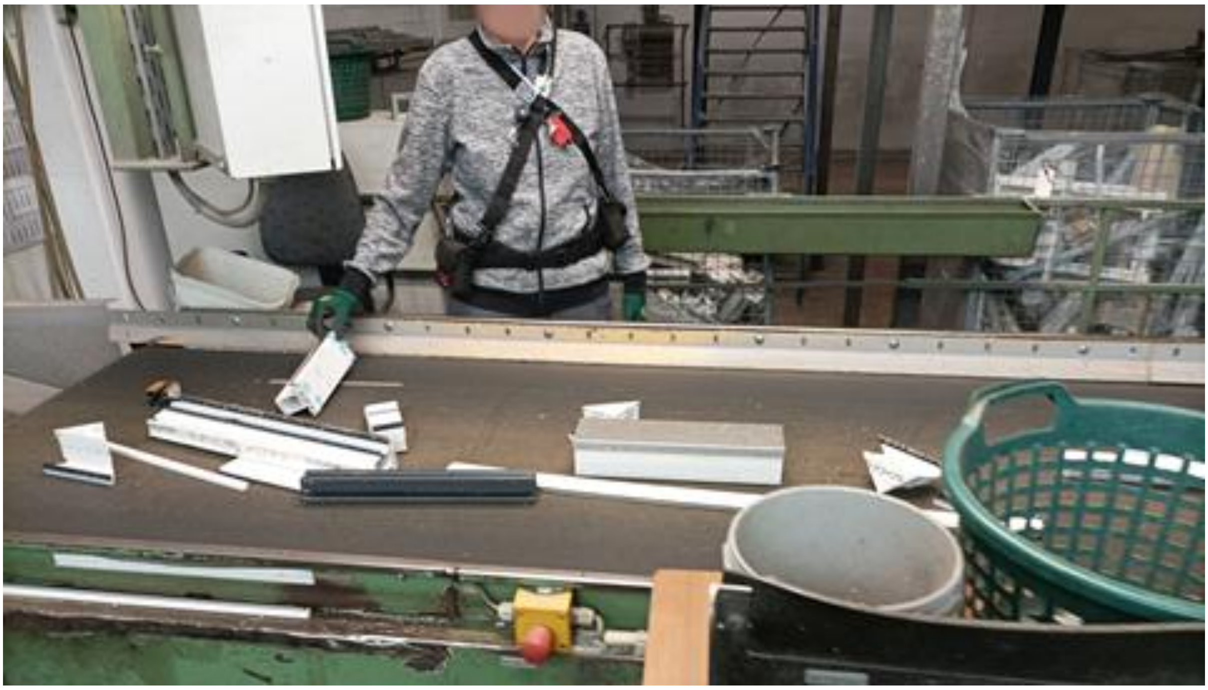


Figure 11 Manual sorting of pre-consumer waste at plant B

Post-consumer waste treatment starts outside of the plant in a large pre-shredding facility and initial sorting step. Here operators feed the bulky post-consumer waste into a shredder (Figure 10 left) which is designed to reduce the size of profiles to several tens of centimetres (Figure 13 left). Glass treated in the same way shatters to a far smaller size. The larger profile pieces are separated from smaller material by sieving.

Figure 12 Preshredder treatment of smaller material fraction. Left: Magnetic separator. Right: additional sorter.

Smaller material passes a magnetic sorting step to recover metals (Figure 12 left) and afterwards an additional sorter to separate glass and the remaining material. The metal and glass are sold for further processing in the metal and glass recycling industry. The remaining material (Figure 13 right) is fed into the indoor mechanical recycling process after the indoor shredding step.

Figure 13 Main output of the pre-shredder process. Left: larger profile pieces being shovelled into the indoor shredding process. Right: the finer output of the pre-shredder processing ready for introduction into the indoor mechanical process.

Following the indoor shredding process, the material stream is reduced to a smaller size. At the point where the material enters the hall in which post-consumer mechanical processing line is located, an over-band air extraction system is in place. Such extraction points are located throughout the plant, and nearly all output point of any treatment steps are equipped with extraction ventilation. The purpose of these extraction points is twofold: 1) it removes dust and foamed material from the waste stream and 2) it reduces the airborne dust concentration in the plant.

All air extraction points are connected to a centralised air cleaning system that is specifically designed to remove the dust and foamed material prior to expelling the air to the environment (Figure 14). A proportion of the captured dust is microplastics. This proportion will increase throughout along the process as more non plastics material is removed at process each step. The dust and microplastics captured are thus removed from the air stream and carefully directed towards final disposals limiting environmental release of these particles.

Figure 14 Air Extraction and filtering system. Left: the bottom view of the air extraction system with the big bag collecting the material removed from the air stream. Right: the inside of the big bag showing the dust and foamed or otherwise light material.

Following the shredding and initial dedusting, ferrous metal is removed by an over-band magnet (Figure 15). Following this ferrous metal separation, there is equipment to introduce the finer material from the pre-shredder process.

Figure 15 Magnetic sorting of shred profile waste. Left: shred material stream passing over magnet to remove ferrous metals. Right: separated ferrous metal.

The material streams are treated subsequently with eddy current separation to remove non-ferrous metals (Figure 16) and/or optical sorting to remove other non-targeted materials such as residual glass (Figure 17).

Figure 16 Eddy current separation. Left eddy current separator. Right: material removed from waste stream.

Figure 17 Optical Sorter. Left: Optical Sorter. Right: material removed from waste stream

Following the removal of non-ferrous metals and a large fraction of residual glass, the material is passing through a density sorting step to remove material of low density.

The waste stream is subsequently ground and consists primarily of: white and coloured PVC and rubber. Impurities such as glass, and to a lesser extend residual metals, may still be present. The material is moved to a silo for further processing in the electrostatic sorting hall.

In the electrostatic sorting hall, material from both the pre-consumer and post-consumer mechanical processing lines are processed by mainly electrostatic sorting to produce a rubber waste fraction and one or more qualities of (coloured) PVC regrind.

Following the separation into a PVC regrind stream, the material is either extruded with melt filtration (vast majority of output) or processed by micronization (minor fraction of output).

In extrusion with melt filtration, the regrind is introduced into a screw filled tube and crushed by the turning screw (see Figure 18 left). The crushing and friction caused by the turning screw causes heat formation and the melting of the regrind. The molten plastics phase is passed through a metal sieve to remove non-melting parts which can include all impurities inherent to the waste stream: rubber, metals, glass, wood, and other polymers with a higher melting point[3]. The filters periodically gets saturated with such non-PVC materials and is cleaned/replaced by the extrusion line operators. This results in filter cakes which are disposed of or are further processed by micronization.

Normally extrusion with melt filtration also allows for a degree of compounding, i.e. addition of virgin PVC or additives to improve the performance of the material. In Plant B, the addition of additives was relatively limited and at the moment of the visit was limited to an internal lubricant to improve the flow of material in the Plant's and the customer's processing equipment.

Figure 18 Equipment in Extrusion Hall. Left: Extrusion equipment with Melt-Filtration. Right: pellet cooling tower.

Following the extrusion step, the pellets are transported by air current in closed tubing towards a cooling tower, where the pellets are gently cooled under light agitation and air current (Figure 18 right), before being transported to a big bag filling station. Operators periodically transport filled big bags on pallets by forklift truck to a storage hall ready for transport to customers and place empty big bags in the filling stations.

Risk Assessment for Human Health

There are 16 workers normally operating this plant:

- 4 outdoor pretreatment operators
- 4 pre-consumer line operators
- 2 post-consumer line operators
- 2 electrostatic sorting department operators
- 4 extrusion line operators

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[3] In fact, PVC is a polymer with one of the lowest melting points meaning that melt filtration is particularly effective at removing of residual non-PVC polymers. Furthermore, it makes PVC a polymer that requires relatively less energy to process compared to other thermoplastics.

Of the outdoor pre-treatment operators two operate heavy vehicles one wheel loader and one crane fitted with a grapple that ensure continuous supply of the shredder. Another two operate forklift trucks and exchange full containers of various waste or side products with empty ones and ensure delivery of materials to their respective destinations. Operators from this pool also assist in the unloading process of tipping trucks (e.g. telling the truck drivers where to tip their loads). 1 Heavy vehicle operator and 1 forklift truck operator were included in the measurement campaign (labelled “Post Consumer (outside)”).

In the pre-consumer department: 1 operator was in charge of feeding the line with specific heavy equipment, 2 were performing manual sorting, and sometimes 1 is assigned to the micronization sub-department. As explained above, only minor quantities of material are micronized, and the process is substantially automated. As such manual sorting operators were deemed to have the highest exposure potential and 1 such operator was included in the measurement campaign (labelled “Pre Consumer”).

The two operators in the post-consumer department had different roles. One was in charge of feeding the line with raw material and another went up and down the line by forklift truck making sure equipment was running properly and exchanging filled containers capturing the various waste outputs. Given the different roles, both were included in the measurement campaign (labelled “Post Consumer)”.

The two electrostatic sorting department operators both move around the hall checking equipment and exchanging containers with waste and side products and changing big bags at various points in the process. Given the similar exposure pattern only one was included in the measurement campaign (Labelled “Electro-Static Sorting”).

Of the extrusion line operators, 3 were directly assigned to their own extrusion line and there was a supervisor that in general has a slightly greater distance to the production equipment. As the lines are identical in terms of exposure potential, a single non-supervisor extrusion line operator was included in the study (labelled “Extrusion Operator”).

Dust

Plant B provided exposure measurement reports containing information on respirable and inhalable dust concentrations as well as lead and cadmium concentrations in the workplace air. These measurements were performed by an external service provider that uses a national standard to perform such measurements that differs from the methodology used in this study and are thus not necessarily comparable. The results are included in Table 9 and reveal the impact in investments performed over the past years in extraction ventilation/dedusting systems at plant B.

Table 9 Previously performed measurements of respirable and inhalable dust (mg/m^3) according to national standards. NA = Not available.

Dust Type	Location	2018	2020	2021	2022	2024
Inhalable	Post Consumer	4.7	23.1	8.1	2.7	1.4
	Electrostatic Sorting	2.9	7.7	3.9	4.4	2.3
	Extrusion	1.3	NA	2.9	0.6	0.9
Respirable	Post Consumer	0.5	0.9	0.5	0.3	0.3
	Electrostatic Sorting	0.4	1.1	0.6	0.1	0.3
	Extrusion	0.4	NA	0.6	0.2	0.2

Dust measurements performed in the context of this study in Plant B revealed that all workers were exposed to respirable and inhalable dust below the limit values adopted for this report of 1 and 5 mg/m^3 for respirable and inhalable dust respectively (see Table 32 for results and Table 32 for raw measurement data). As such there is no adverse effect expected from exposure to dust.

Table 10 Results of the respirable and inhalable dust measurements in Plant B and Risk Characterisation Ratios (RCR) based on a limit of 1 mg/m³ for respirable and 5 mg/m³ for inhalable dust. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red. NA = Not Available (the pump for respirable dust failed).

ID	Sample Description	Sampling Time (min)	Respirable (mg/m³)	RCR	Inhalable (mg/m³)	RCR
B1	RS - Post Consumer (Outside)	401	0.09	0.09	0.44	0.09
B2	SP - Post Consumer (Outside)	406	NA	NA	0.35	0.07
B3	JD - Post Consumer	347	0.09	0.09	0.66	0.13
B4	CC - Post Consumer	341	0.11	0.11	0.74	0.15
B5	SS - Pre Consumer	344	0.09	0.09	0.38	0.08
B6	BS - Electro-Static Sorting	370	0.31	0.31	0.71	0.14
B7	HS - Extrusion Operator	360	0.10	0.10	0.37	0.07

Relatively higher exposure was observed in the operators of the post-consumer line and the electrostatic sorting department, where there is mechanical sorting of materials. The lower exposure is logical since: 1) the outside operators spend the majority of their time in the cabin of a vehicle with fresh somewhat filtered air supply, 2) the pre-consumer material on the manual sorting station is relatively clean and in big parts, and 3) the extrusion process is mainly a closed process in which there is not strong agitation of the material.

Lead and Cadmium

Similarly to inhalable and respirable dust, Plant B was able to supply measurement data for lead and cadmium going back a number of years (Table 11). Likewise, the measurements were performed by an external service provider that used different national standard methods and results should not be compared to the measurements taken in this study. These results reveal a similar downward trajectory due to improvements in risk management measures.

Table 11 Previously performed measurements of lead and cadmium in inhalable dust fraction (µg/m³). NA = Not available.

Parameter	Location	2018	2020	2021	2022	2024
Lead	Post Consumer	13	87	13	9	4
	Electrostatic Sorting	8	19	8.7	14	7.5
	Extrusion	2	NA	5.2	1.5	0.2
Cadmium	Post Consumer	NA	NA	0.62	0.24	0.18
	Electrostatic Sorting	NA	NA	0.40	0.83	0.37
	Extrusion	NA	NA	0.24	0.06	<0.1

Measurements performed for the purpose of this study reveal lead and cadmium concentrations in Plant B well below their occupational exposure limits in the CMRD (see Table 12 for results and Table 32 for raw measurement data).

Table 12 Results of the cadmium and lead in inhalable dust measurements in Plant B and Risk Characterisation Ratios (RCR) based on a limit of 1 µg/m^3 for cadmium and 30 µg/m^3 for lead. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Pb (µg/m^3)	RCR	Cd (µg/m^3)	RCR
B1	RS - Post Consumer (Outside)	401	0.224	0.007	0.008	0.01
B2	SP - Post Consumer (Outside)	406	0.164	0.005	0.006	0.01
B3	JD - Post Consumer	347	0.766	0.026	0.033	0.03
B4	CC - Post Consumer	341	0.823	0.027	0.038	0.04
B5	SS - Pre Consumer	344	0.222	0.007	0.008	0.01
B6	BS - Electro-Static Sorting	370	0.706	0.024	0.033	0.03
B7	HS - Extrusion Operator	360	0.477	0.016	0.020	0.02

Organotin

No tin was detected in the inhalable dust fraction of Plant B. As such all concentrations are calculated based on the limit of detection of the analytical method which was 50 ng/sample, which translates into various limits of detection for tin (range 0.06 – 0.07 µg/m^3) dependent on the sampled air volume (see Table 13 for results and Table 32 for raw measurement data). The limit of detection was sufficiently low to conclude that the maximum RCRs are sufficiently below 1, indicating that workers in plant B are not at risk from organotin exposure.

Table 13 Results of the tin in inhalable dust measurements and calculation of maximum organotin concentrations in Plant B and Risk Characterisation Ratios (RCR) based on a limit of 25, 180, and 5750 µg/m^3 for DOTE, DMTE, and MMTE. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sn (µg/m^3)	Max DOTE (µg/m^3)	Max DMTE (µg/m^3)	Max MMTE (µg/m^3)	Max DOTE RCR	Max DMTE RCR	Max MMTE RCR
B1	RS - Post Consumer (Outside)	<0.06	<0.37	<0.28	<0.37	<0.01	<0.002	<0.0001
B2	SP - Post Consumer (Outside)	<0.06	<0.37	<0.27	<0.37	<0.01	<0.002	<0.0001
B3	JD - Post Consumer	<0.07	<0.43	<0.32	<0.43	<0.02	<0.002	<0.0001
B4	CC - Post Consumer	<0.07	<0.44	<0.33	<0.44	<0.02	<0.002	<0.0001
B5	SS - Pre Consumer	<0.07	<0.44	<0.32	<0.44	<0.02	<0.002	<0.0001
B6	BS - Electro-Static Sorting	<0.06	<0.41	<0.3	<0.4	<0.02	<0.002	<0.0001
B7	HS - Extrusion Operator	<0.07	<0.42	<0.31	<0.42	<0.02	<0.002	<0.0001

Antimony and zinc

Traces of antimony were detected in the dust at levels far below the 250 µg Sb/m^3 limit. Zinc was found at slightly higher concentrations but still well below the 500 µg Zn/m^3 limit. No adverse impact on human health is to be expected from antimony or zinc exposure.

Table 14 Results of the antimony and zinc in inhalable dust measurements in Plant B and Risk Characterisation Ratios (RCR) based on a limit of 250 $\mu g/m^3$ for antimony and 500 $\mu g/m^3$ for zinc. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Sb ($\mu g/m^3$)	RCR	Zn ($\mu g/m^3$)	RCR
B1	RS - Post Consumer (Outside)	401	<0.01	<0.00004	2.48	0.005
B2	SP - Post Consumer (Outside)	406	<0.01	<0.00004	1.52	0.003
B3	JD - Post Consumer	347	0.008	0.00003	10.67	0.021
B4	CC - Post Consumer	341	0.007	0.00003	11.02	0.022
B5	SS - Pre Consumer	344	0.008	0.00003	2.50	0.005
B6	BS - Electro-Static Sorting	370	0.027	0.00011	4.24	0.008
B7	HS - Extrusion Operator	360	0.032	0.00013	5.31	0.011

Environmental Emissions

Channelled Emissions

Dedusting of the material stream is an integral part of the recycling process and the Plant is equipped with a network of piping to carry the air and dust streams to centralised air cleaning systems. These dedusting systems (Figure 14) capture the fines and foamed material into big bags which are sealed and sent for final disposal. The plant was able to provide reports by external service providers that quantified the channelled emissions to air which were in the range of 0.001 to 0.002 kg/h and deemed to be irrelevant compared to other dust emissions.

Since the facility treats roughly 6 – 8 tons per hour, the channelled emissions from Plant B amount to between 0.00001% - 0.00003%.

Diffuse Emissions

The plant was able to provide a report on diffuse emissions that was carried out prior to the measurements performed for this study. An external service provider quantified diffuse dust emissions using VDI 3790-3 and VDI 3790-4 and considered the following emission sources:

- Road movements of trucks on the asphalted surfaces of the plant.
- Unloading of a fraction of packed pre-consumer materials, a fraction of raw material tipped directly into the hall, and the tipping of a fraction of material area dedicated to the receipt of post-consumer material.
- The outdoor shredding of post-consumer material
- The outdoor movement of heavy vehicles to transport the various intermediate and waste material fractions.
- Blowing away of dust from material stored outdoor on the premises.
- Expedition of product and waste fraction by trucks.

To populate the diffuse emission model, the site was visited by the external service provider on a dry clear weather day and the following observation was made and reported in the provided report: *During the site inspection, no noticeable dust development was observed during the operation of the shredding and outdoor sorting system, nor during the arrival and departure of the trucks (dry, clear weather). Nevertheless, to be on the safe side, the treated goods are classified below as imperceptible to slightly dusty.* In other words, the model outcome should be considered to be conservative.

All movements of vehicles assumed amongst other things a light to moderate soiling of the asphalt surface of 3 g/m² and local/national meteorological conditions. For the emission factor of the outdoor shredder an emission factor of 5 – 25 g/t was considered based on BUBE-Online (BUBE). The delivery and pickup of materials assumed a tip height of 1 m and various other material specific factors. The standard indicates that wind erosion from material stored outdoor may be considered negligible if the average annual wind speeds are no more than 3 m/s as measured at a height of 10 meters above the surface. The average measured windspeed at 16 meters was determined to be 2.5 m/s and thus wind erosion was considered to be negligible.

The model determined that the average emission mass flow from the site would be 0.3-0.4 kg/h per week. This was above the level of 0.1 kg/h which according to local regulations would have been considered negligible and not requiring further investigation. This exceedance resulted in the requirement to model the deposition of the dust using more advanced *in silico* modelling. This exercise resulted in a map which has been superimposed on the satellite image for the purpose of this report revealing that the vast majority of all dust deposition occurs on the premises of plant B (see Figure 19). Only a small fraction is released beyond the boundaries of the facility.

To prevent subsequent release of this deposited dust to air by vehicles/wind or to rainwater runoff the company employs a street sweeper vehicle that cleans the premise daily.

Figure 19 plant outline with superimposed dust deposition modelling results. The outer most green section is indicative of a deposition of between 10.5 and 21 mg/m²/d while the inner most dark grey represents a deposition of >105 mg/m²/d.

The diffuse dust emissions from the processes occurring in Plant B have been determined to be 0.3 – 0.4 kg/h, the dust emissions from the facility however will be substantially less than this. Since the facility treats roughly 6 – 8 tons per hour, this would translate to a diffuse emission factor of 0.004 – 0.007 %. Furthermore, not all the dust will be microplastics. As such, the calculated factors are conservative for microplastics emissions from Plant B.

PLANT C

Plant C treats several tens of thousands of tons of construction profile waste per year from both pre- and post- consumer origin. The plant layout can be found in Figure 20. The waste material contains all the typical impurities such as steel, aluminium, glass, PMMA, rubbers, and minerals, with somewhat greater contamination in the post-consumer input vs the pre-consumer input.

Figure 20 Plant C Layout. Blue is outdoor area for receiving & shredding of profile waste; green is indoor building where mechanical processes occur; yellow is indoor building where regrind is extruded with melt filtration to produce pellets; with outdoor silo storage or packaged good storage under canopy.

Material is received in an outdoor area with impermeable surface with rainwater capturing system. The first shredding step occurs outside and is performed by a mobile shredding unit that deposits its output in a next outdoor compartmentalised zone. From this second storage area material is shovelled by a wheel loader into a hopper that conveys the material indoor. See Figure 21 for details.

Figure 21 Left: outdoor storage area for construction profile waste as received with the first mobile outdoor shredder. Right: shredded waste and the hopper that starts the conveyer chain for the indoor processing. Note the forklift truck on the right is equipped with a brush to clean the surface and prevent spread of material to other areas of the plant and beyond.

Once inside, the dedusting of the material starts. There is extraction ventilation installed at a myriad of points in the production process which also reduces the dustiness within the plant and contributes to the limitation of the release of microplastics. The material stream will then pass by a magnetic separator to remove ferrous metals before being transported to a sieve that produces three distinct streams characterized by different particle size distributions. See Figure 22.

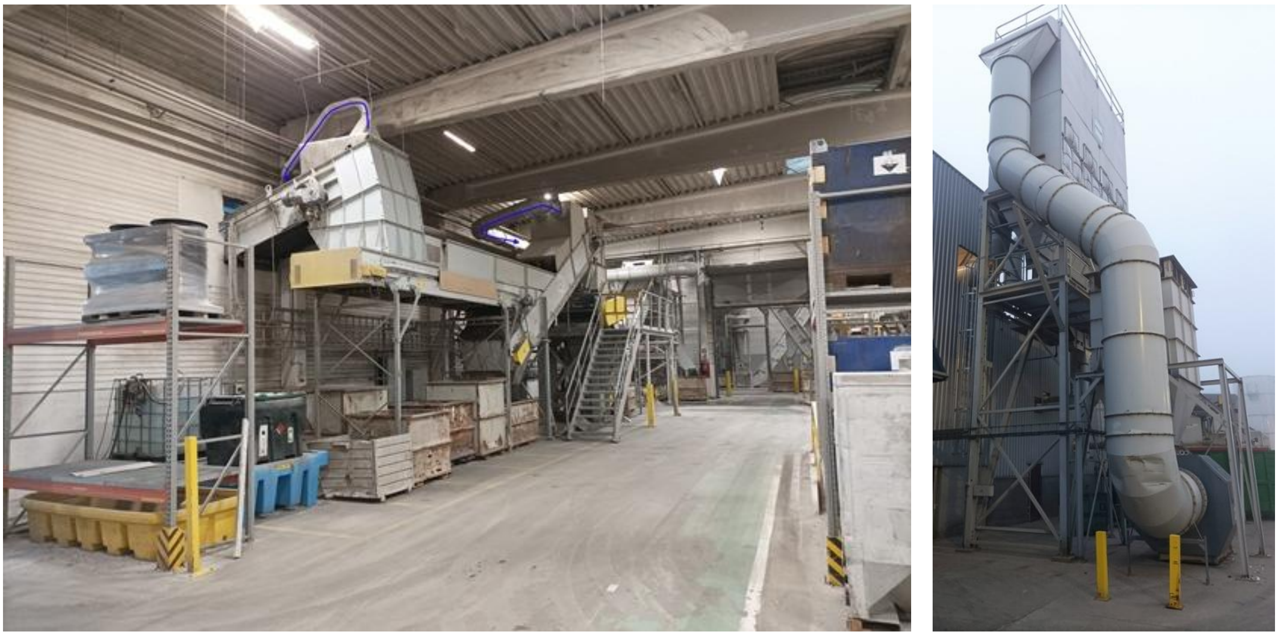

Figure 22 Left: Material stream entering the building and passing first magnetic separator. Blue arrows indicate the flow of air and dust in the extraction system. Right: the air cleaning system.

Following the initial dedusting and metal separation steps, the material is sieved and divided into three distinct size fractions (Figure 23 left) that are further processed in much the same way in a mechanical separation system that uses magnetism, eddy current separation, and other techniques to remove metals and glass from the waste stream (Figure 23 right). The remaining material will contain primarily PVC and rubber, light material (e.g. wood), and mineral contamination.

Figure 23 Left: Sieve System. Right: the first mechanical sorting system for the three size fraction streams.

Subsequently all three size fractions are recombined and directed to a wet milling process and wet density separation process that removes light materials (e.g. wood) and minerals from the waste stream (Figure 24). The process water is treated on-site in a water treatment process that enables the recycling of the process water (Figure 25). In doing so, sludge is generated which is mainly due to the mineral impurities in the waste stream.

Figure 24 Left: wet grinding and density separation equipment. Right: material separated from the waste stream through density separation equipment.

Figure 25 Left: Process water cleaning system and reagents used to in the process. Right: sludge which is mainly the mineral impurity removed from the waste stream.

Following this step, the material stream consists primarily of PVC and rubber (and trace levels of all previous impurities). This material stream is subsequently dried and subjected to grinding to obtain material of a more uniform small size distribution that is subsequently transported to silos by piping systems. This material is subsequently further sorted with the aid of electrostatic sorting- and colour sorting- equipment (Figure 26) to produce: a white PVC regrind, a coloured PVC regrind, and a waste rubber fraction. These regrind product fractions are moved to silos.

Figure 26 Left: Electrostatic sorting equipment. Note the presence of cleaning equipment to prevent the spread of microplastics. Right: colour sorting equipment.

Finally, the PVC fractions are pulled from the silo to be processed by extrusion with melt filtration (Figure 27 left). The plant also performs compounding in this step, meaning that additives are fed into the extruder for homogenisation with the material in the melt phase. These additives improve the physical mechanical properties of the material. The warm pellets are cooled in an active way with air in dedicated equipment (Figure 27 Right).

Figure 27 Left: extrusion with melt filtration equipment and operator cleaning in between the melt filter change cycles. Right: the active pellet cooling equipment.

Risk Assessment for Human Health

There are 4 – 9 workers normally operating this plant:

- 1 – 2 outdoor operators
- 1 – 2 mechanical sorting operators
- 1 electrostatic/colour sorting department operator
- 1 – 4 extrusion line operators

The outdoor operators operate heavy vehicles such as a mobile crane vehicle to grab rough construction profile waste and feed the outdoor shredder or a wheel loader to shovel the shredded PVC into a hopper which transports the material into the plant.

The mechanical sorting operators work in the area where all steps are performed before the material is subjected to grinding. They inspect the equipment to ensure proper functioning and drive around in forklift trucks to empty the containers that capture the various material fractions that are extracted from the materials stream (e.g. ferrous metals, non-ferrous metals, light materials, and sludge).

The electrostatic/colour sorting operator manages the proper operation of this department. Inspecting machinery and driving in a forklift truck to move around big bags which are used to capture minor fractions (e.g. the rubber waste fraction).

There is the greatest variability in the number of extrusion line operators because the number of extrusion lines that operate at any given time is dependent on demand by downstream industries. One operator can ensure the functioning of 1 – 2 extrusion lines. The primary operation on the line is the periodic replacement of melt filters, which requires removal of the filter cake by scraping, followed by removal of the metal mesh filter and replacement by a new filter. The line is equipped with two such filters and when one is being replaced the other is used to ensure continuous operation of the equipment.

Dust

Dust measurement revealed that the outdoor shredding operators, the mechanical sorting operators, and electrostatic/colour sorting operator, were operating in dust levels that are below the limit values adopted for this report (1 and 5 mg/m^3 for respirable and inhalable dust). The airborne concentration measured on the extrusion operator however exceeded the inhalable dust limit value. This elevated airborne concentration is related to periodic cleaning activities that were performed during the part of the shift during which the measurement occurred (see Figure 27 left). It was known to the plant and the operator in question that this activity is associated with increased dust formation and thus respiratory protective equipment was used (half mask respirator with P3 filter). For the quantitative analysis the mask is assumed to reduce exposure by a factor of 10, meaning that the exposure behind the mask is calculated to be 3.1 mg/m^3 and thus below the limit of 5 mg/m^3, meaning the operator is working safely.

Table 15 Results of the respirable and inhalable dust measurements in Plant C and Risk Characterisation Ratios (RCR) based on a limit of 1 mg/m^3 for respirable and 5 mg/m^3 for inhalable dust; assuming a protection factor of 10 when RPE is used. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Respirable (mg/m^3)	RCR	Inhalable (mg/m^3)	RCR
C1	Shredder Operator	292	<0.08	<0.08	0.31	0.06
C2	Mechanical Sorting Operator	219	<0.10	<0.1	0.43	0.09
C3	Electrostatic/Colour Sorting Operator	191	<0.12	<0.12	2.28	0.46
C4	Extrusion Operator (Mask)	202	0.45	0.045	30.62	0.61

The plant was also able to provide a measurement report of recent exposure measurements they had performed themselves. Not only did the external service provider that performed the sampling used the same method for the sampling/analysis, but they were also using the same laboratory for the analysis. As such these measurements should be highly comparable. The only deviation was that only inhalable dust was measured (not respirable) and not all elements included in this study were quantified; only the most relevant: lead and cadmium.

These measurements (Table 16) reveal that under normal conditions inhalable dust levels in extrusion were 0.36 – 0.45 mg/m^3, well below the 5 mg/m^3 limit. The results for the Electrostatic/Colour Sorting Operator were comparable to the were comparable to the measured values of the current study. The mechanical sorting operator measurement in the late shift was similarly in line with the measured value of the current study, however there is an elevated concentration exceeding the limit during the early shift. The high measurement during the early shift in mechanical sorting occurred at the time when mechanical cleaning was being performed with large brushes; half mask respirators with P3 filters are worn during such activities and keep exposure well below the limit of 5 mg/m^3.

Table 16 Results of the plants own inhalable dust measurements in Plant C and Risk Characterisation Ratios (RCR) based on a limit of 1 mg/m^3 for respirable and 5 mg/m^3 for inhalable dust; assuming a protection factor of 10 when RPE is used. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Inhalable (mg/m^3)	RCR
C5	Mechanical Sorting Operator (Early Shift)(mask)	163	7.56	0.15
C6	Mechanical Sorting Operator (Late Shift)	131	0.92	0.18
C7	Static in Mechanical Sorting	302	0.61	0.12
C8	Electrostatic/Colour Sorting Operator (Early Shift)	194	3.93	0.79
C9	Electrostatic/Colour Sorting Operator (Late Shift)	122	1.50	0.30
C10	Static on Electrostatics Sorting	317	0.28	0.06
C11	Extrusion Operator (Early Shift)	180	0.36	0.07
C12	Extrusion Operator (Late Shift)	179	0.45	0.09
C13	Static in Extrusion Department	306	0.23	0.05

Lead and Cadmium

Quantification of lead and cadmium resulted in the finding that for the shredder, mechanical sorting, and electrostatic sorting operators the exposure is well below the limit values. The airborne concentration of lead and cadmium in the breathing zone of the extrusion operator exceeds the limit values. However, with the mask worn the calculated exposure using a protection factor of 10 would be 7.9 µg Pb/m^3 and 0.6 µg Cd/m^3, which is below the limit of 30 and 1 µg/m^3 for lead and cadmium, indicating that this worker operates safely.

Table 17 Results of the cadmium and lead in inhalable dust measurements in Plant C and Risk Characterisation Ratios (RCR) based on a limit of 1 µg/m^3 for cadmium and 30 µg/m^3 for lead; assuming a protection factor of 10 when RPE is used. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Pb (µg/m^3)	RCR	Cd (µg/m^3)	RCR
C1	Shredder Operator	292	<0.341	<0.011	<0.17	<0.17
C2	Mechanical Sorting Operator	219	0.980	0.033	<0.227	<0.23
C3	Electrostatic/Colour Sorting Operator	191	0.788	0.026	<0.262	<0.26
C4	Extrusion Operator (Mask)	202	79.506	0.265	5.926	0.59

The plant's own measurements of lead and cadmium can be found in Table 18 and show compliance with the occupational exposure limits for lead and cadmium in all working positions.

Table 18 Results of the cadmium and lead in inhalable dust measurements performed by Plant C and Risk Characterisation Ratios (RCR) based on a limit of 1 µg/m^3 for cadmium and 30 µg/m^3 for lead; assuming a protection factor of 10 when RPE is used. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Pb (µg/m^3)	RCR	Cd (µg/m^3)	RCR
C5	Mechanical Sorting Operator (Early Shift) (mask)	163	6.95	0.023	<0.3	<0.03
C6	Mechanical Sorting Operator (Late Shift)	131	1.80	0.060	<0.38	<0.38
C7	Static in Mechanical Sorting	302	1.21	0.040	<0.16	<0.16
C8	Electrostatic/Colour Sorting Operator (Early Shift)	194	2.56	0.085	<0.26	<0.26
C9	Electrostatic/Colour Sorting Operator (Late Shift)	122	2.73	0.091	<0.41	<0.41
C10	Static on Electrostatics Sorting	317	0.68	0.023	<0.12	<0.12
C11	Extrusion Operator (Early Shift)	180	<0.55	<0.018	<0.28	<0.28
C12	Extrusion Operator (Late Shift)	179	1.52	0.051	<0.28	<0.28
C13	Static in Extrusion Department	306	0.35	0.012	<0.16	<0.16

Organotin

Tin was detected in the inhalable dust present in the breathing zone of the operator performing extrusion, but not any other operator. The detection is likely due to the relatively high dust concentration in the breathing zone of this worker. The mass concentration of tin in this dust was 0.002% and thus can be considered very low. In any case, even without mask the RCRs are below 1 indicating that there is no risk. When taking the mask into consideration the highest RCR would be 0.02.

Table 19 Results of the tin in inhalable dust measurements and calculation of maximum organotin concentrations in Plant C and Risk Characterisation Ratios (RCR) based on a limit of 25, 180, and 5750 µg/m^3 for DOTE, DMTE, and MMTE; assuming a protection factor of 10 when RPE is used. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sn (µg/m^3)	Max DOTE (µg/m^3)	Max DMTE (µg/m^3)	Max MMTE (µg/m^3)	Max DOTE RCR	Max DMTE RCR	Max MMTE RCR
C1	Shredder Operator	<0.17	<1.08	<0.8	<1.07	<0.04	<0.004	<0.0002
C2	Mechanical Sorting Operator	<0.23	<1.44	<1.06	<1.42	<0.06	<0.006	<0.0002
C3	Electrostatic/Colour Sorting Operator	<0.26	<1.66	<1.22	<1.64	<0.07	<0.007	<0.0003
C4	Extrusion Operator (Mask)	0.679	4.300	3.177	4.254	0.017	0.002	0.0001

Antimony and zinc

Traces of antimony were detected in the dust at levels far below the 250 µg Sb/m^3 limit. Zinc was found at slightly higher concentrations but still well below the 500 µg Zn/m^3 limit. No adverse impact on human health is to be expected from antimony or zinc exposure.

Table 20 Results of the antimony and zinc in inhalable dust measurements in Plant A and Risk Characterisation Ratios (RCR) based on a limit of 250 µg/m³ for antimony and 500 µg/m³ for zinc; assuming a protection factor of 10 when RPE is used. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Sb (µg/m³)	RCR	Zn (µg/m³)	RCR
C1	Shredder Operator	292	<0.17	<0.00068	2.59	0.005
C2	Mechanical Sorting Operator	219	<0.23	<0.00092	4.61	0.009
C3	Electrostatic/Colour Sorting Operator	191	<0.26	<0.00104	<2.62	<0.005
C4	Extrusion Operator (Mask)	202	0.435	0.00017	14.81	0.003

Environmental Emissions

Channelled Emissions

As explained in the plant description in the section above, dedusting is an integral part of the recycling process with air extraction taking place at a myriad of points in the process. All these points are funnelled to a centralised air cleaning systems and stack. The company periodically measures the dust emission in this stack (see Table 21). The emissions of the plan are around 42 g/h, while the facility treats 3 - 5 tons/hour. As such between 0.0008 and 0.0014% of material is emitted via channelled emissions to air.

Table 21 Centralised Stack Emissions Plant C.

Stack Parameter	Centralised Stack
Flow rate (m/s)	18.6
Flow rate (m³/h)	95304
Total Dust (mg/m³)	0.44
Total Dust (kg/h)	0.0416
Total Dust (g/h)	41.6

Diffuse Emissions

Diffuse emissions are rather difficult to impossible to quantify. However, Plant C is cognisant that these are to be prevented and/or minimised whenever possible. The entire facility including the waste storage area has an impermeable surface with a collection system for rainwater runoff, which is filtered before being emitted. However, more importantly, Plant C has deployed several practices to prevent (micro)plastics from reaching the rainwater collection system.

One technology used by Plant C is to regularly sweep the terrain with forklift mounted brushes and even a street cleaning truck (see Figure 28). With this technology, passageways for heavy vehicles are kept clean and this prevents the spread of (micro)plastics on the lot and beyond (see Figure 29). Next to this, Plant C has invested in a variety of equipment ranging from simple brushes, to vacuum cleaning equipment, to street cleaning vehicles to keep the plot clean. Input waste material is stored in bunkers that are surrounded by concrete walls to prevent spread as well.

Figure 28 Street cleaning car used by plant C.

Figure 29 Forklift mounted brushes employed by Plant C. Left, a forklift in operation cleaning the passage ways between the stored waste and the feeding equipment. Right, a close up of the mountable brushes.

Figure 30 Cleaning technology owned and used by Plant C

Plant staff was also observed to actually use this equipment to clean spillages of material such as (micro)plastics and were using it during the site visit (see for example Figure 27 where an operator in extrusion using the equipment).

PLANT D

Plant D treats all sorts of rigid plastics waste, primarily post-consumer waste material originating from civic amenities sites[4]. However, they also receive a wide variety of specific waste material streams such as: crates and pallets, cleaned industrial containers (e.g. IBCs and drums), coat hangers, flowerpots, garden furniture, and important for this project: construction profiles and PVC pipes. On the day of the measurement, they had built up stock of PVC pipes to run a full production run of this material. Normally such runs are not everyday events or there are different materials treated in the same shift. As such, all conclusions on risk and exposure are relatively worst case.

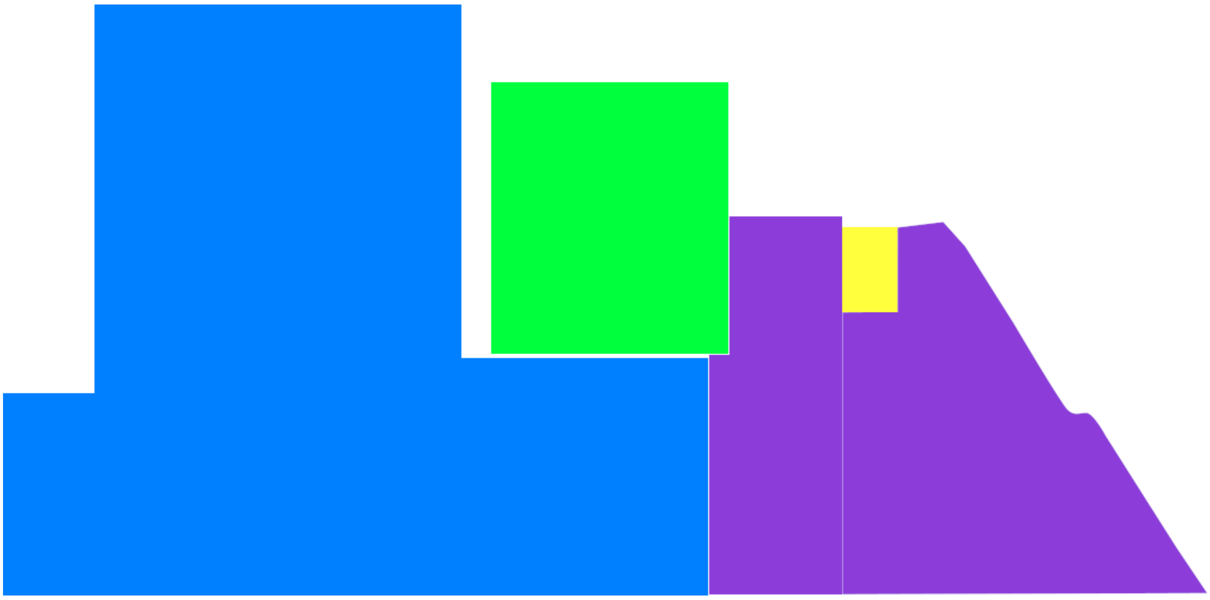

Figure 31 Plant D Layout. Highlights: waste receipt and storage (blue), mechanical sorting and size reduction (green), PVC micronization hall (yellow), and finished product storage (purple).

Different waste material streams are received in an outdoor area with a paved surface. Given the wide variety of different waste input materials the company has a great many compartments built out of thick concrete. The concrete barriers are primarily erected to contain fire spread should this occur; however, it also forms a barrier to the release of (micro)plastic material to the surrounding area.

For relatively homogeneous waste materials that do not require manual sorting or have already undergone manual sorting that is in a bulky state such as the PVC pipe waste, the first processing step is outdoor shredding using a mobile shredder and other heavy vehicles to shovel the material into a compartment designated for the shredded material (see Figure 32).

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[4] Civic amenities sites are locations, typically organized by municipalities that organize the collection of bulky wastes. Citizens can bring their bulky waste by car and deposit it in designated containers. FR: Déchèterie, DE: Recyclinghof, NL: Milieupark.

Figure 32 Left: crane feeding outdoor shredder. Right: output fractions of the outdoor shredder.

The shredded bulky PVC pipe waste will contain primarily rigid PVC but rubbers (albeit to a lower level than profiles since only fittings sometimes contain rubbers), ferrous and non-ferrous metals, and minerals (i.e. dirt). The ferrous and non-ferrous metals are removed by magnetic and eddy-current separation techniques. Following this the material is washed and dedusted. =. Finally, the material is passed on a conveyer past an operator that performs a visual quality check and manually removes shreds of material that do not belong in the waste stream (see Figure 33).

Figure 33 Left: big bag feeding station of the grinding hall. Right: Operator performing visual check of grinder input.

The water cleaning step is naturally resulting in process wastewater. This water is treated on site and reused following the cleaning. The resulting sludge is sent for disposal.

Following the manual sorting operation, the material is fed into a grinder, the output of which forms the first product fraction of the plant: PVC regrind. Such regrind can be used by some converters that have slightly higher tolerances for larger particle impurities; though there are also other recycling operators that purchase such regrind and process it further with extrusion and melt filtration to arrive to a pellet that can be used in all relevant plastic conversion processes.

The plant has the capacity to further process the regrind by micronization. With micronized PVC, all the material PVC and the impurities are reduced to a fine powder. This micronized PVC can be used by converters and the impurities that would be removed in an extrusion with melt filtration process simply become a filler-like part of the produced articles. Articles thus produced may have slightly lower physical mechanical properties compared to the same articles produced out of PVC that has undergone extrusion with melt filtration, due to the filler-like content. However, material that has gone through a heating and cooling cycle will also have experienced some degradation that one would not observe when the material is micronized.

Both regrind and micronized product output are stored in sealed big bags outside in anticipation to expedition.

Risk Assessment for Human Health

In the part of the plant that treated the PVC Pipe waste there are normally:

- 1 (- 2) outdoor operators
- 1 mechanical sorting operator
- 1 – 2 micronisation operators

The main outdoor operator operated the crane that picked up the bulky pipe waste and fed it into the outdoor shredder. Periodically a colleague assisted in the moving of the shredded material to a dedicated location, while the majority of his/her time they spent on other tasks elsewhere. Given the greater proximity and longer participation in the work with the PVC pipes, the outdoor operator working on the crane was included in the study.

The mechanical sorting operator spent roughly 80% of his time watching the conveyer belt and picking out non-PVC material. The other 20% of his time, he stopped the conveyer to carry out tasks such as changing big bags and removing containers with waste material. Much of this work carried out on forklift truck. This operator was included in the study.

On the day of the study, the plant was treating PVC Pipes and directing the majority of the output to micronization. As such the activity rate in the micronization department required the two micronization operators. These operators: a) ensured the proper functioning of the equipment, b) brought in big bags with PVC regrind and placed these on hoppers feeding the equipment, and c) removed big bags containing micronized PVC. Given that this process step is the most inherently dusty (the output of the process is a fine dust), both operators were included in the measurement campaign[5].

Dust

All workers were exposed to inhalable and respirable dust below the limits defined in this report of 5 and 1 mg/m^3, respectively (see Table 22). No adverse effect is expected from exposure to dust.

Table 22 Results of the respirable and inhalable dust measurements in Plant D and Risk Characterisation Ratios (RCR) based on a limit of 1 mg/m^3 for respirable and 5 mg/m^3 for inhalable dust. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Respirable (mg/m^3)	RCR	Inhalable (mg/m^3)	RCR
D1	MoH – Outdoor Operator	291	<0.08	<0.08	0.17	0.03
D2	RL – Mechanical Sorting Operator	276	<0.08	<0.08	0.34	0.07
D3	KC – Micronisation Operator	332	<0.07	<0.07	0.23	0.05
D4	RZ – Micronisation Operator	275	<0.08	<0.08	0.22	0.04

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[5] It has to be noted here that, while the process step was the most inherently dusty, the containment of the process was built to match. There were no observable dust clouds being generated in the micronization hall.

Counterintuitively, the higher exposure was observed by the mechanical sorting operator rather than by the micronization operators. However, this can be explained by the fact that given the extremely dusty nature of the micronization process, the containment of the processing equipment was built to match. All operations to the material occurred in closed systems. The fact that the outdoor shredder operator had the lowest exposure is also understandable since he/she spent most of the time in the closed air conditioned cabin of his crane.

Lead and Cadmium

No cadmium was detected in the inhalable fraction and the lead concentrations remained very well below the EU occupational exposure limit as included in the CMRD (see Table 23).

Table 23 Results of the cadmium and lead in inhalable dust measurements in Plant D and Risk Characterisation Ratios (RCR) based on a limit of 1 $\mu g/m^3$ for cadmium and 30 $\mu g/m^3$ for lead. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Pb ($\mu g/m^3$)	RCR	Cd ($\mu g/m^3$)	RCR
D1	MoH - Outdoor Operator	291	0.070	0.002	<0.009	<0.01
D2	RL - Mechanical Sorting Operator	276	0.670	0.022	<0.009	<0.01
D3	KC - Micronisation Operator	332	0.934	0.031	<0.008	<0.01
D4	RZ - Micronisation Operator	275	0.424	0.014	<0.009	<0.01

Organotin

Detectable levels of tin were found in the inhalable dust of the outdoor operator, the mechanical sorting operator and one of the two micronization operators. The calculated maximum organotin concentrations were well below their respective toxicological benchmarks; indicating that there is no unacceptable risk to human health.

Table 24 Results of the tin in inhalable dust measurements and calculation of maximum organotin concentrations in Plant D and Risk Characterisation Ratios (RCR) based on a limit of 25, 180, and 5750 $\mu g/m^3$ for DOTE, DMTE, and MMTE. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	**Sample Description**	**Sn ($\mu g/m^3$)**	**Max DOTE ($\mu g/m^3$)**	**Max DMTE ($\mu g/m^3$)**	**Max MMTE ($\mu g/m^3$)**	**Max DOTE RCR**	**Max DMTE RCR**	**Max MMTE RCR**
D1	MoH - Outdoor Operator	0.447	2.829	2.090	2.799	0.113	0.012	0.000
D2	RL - Mechanical Sorting	1.178	7.457	5.509	7.377	0.298	0.031	0.001
D3	KC - Micronisation Operator	0.512	3.243	2.396	3.208	0.130	0.013	0.001
D4	RZ - Micronisation Operator	<0.09	<0.58	<0.43	<0.57	<0.02	<0.002	<0.0001

The detection of tin in these samples is congruent with the understanding that for the creation of fittings, organotins have been and are still today used. To the best of our knowledge different organotins have been used in this application interchangeably (to a degree) meaning that the calculated maximum concentrations are likely to be overestimates of the exposure to the individual organotins, as the tin concentration in the dust is likely a result of a mixture of different organotins.

Antimony and zinc

Levels of antimony and zinc in the inhalable dust remained well below the limits used in this report. No adverse impact is expected from antimony or zinc exposure.

Table 25 Results of the antimony and zinc in inhalable dust measurements in Plant D and Risk Characterisation Ratios (RCR) based on a limit of 250 µg/m³ for antimony and 500 µg/m³ for zinc. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red.

ID	Sample Description	Sampling Time (min)	Sb (µg/m³)	RCR	Zn (µg/m³)	RCR
D1	MoH - Outdoor Operator	291	0.010	0.00004	<0.86	<0.002
D2	RL - Mechanical Sorting Operator	276	0.016	0.00006	1.03	0.002
D3	KC - Micronisation Operator	332	<0.01	<0.00004	<0.75	<0.002
D4	RZ - Micronisation Operator	275	0.236	0.00095	<0.91	<0.002

Environmental Emissions

Channelled Emissions

Plant D has a centralised extraction and air cleaning installation for the mechanical treatment and grinding hall as well as four separate extraction and air cleaning systems for the micronization hall (see Figure 34). The dust captured with this technology is stored in big bags and sent for disposal.

Figure 34 Air extraction and air cleaning systems of Plant D.

In 2020 an accredited external service provider performed measurements to quantify the dust in the emitted in the cleaned air. In their report, three measurements were taken in the stacks over a period of around an hour and averages were calculated for the dust concentration and dust mass flow from the stacks. Their report indicates that there is an emission dust concentration limit applicable to the individual stacks of the plant of is 5 mg/m³, which is exceeded by one of the micronization extraction points and recommended further investigation/improvement[6].

Following this report in 2020, the plant performed its investigation and improvement program and another measurement revealed that that the emissions from the micronization extraction system had decreased to levels acceptable under national legislation. The improvement thus reduced the total emission from 144 g/h to 21 g/h.

With a total emission of 21 g/h, and a waste processing rate of 1 – 3 tons per hour, the process channelled emission factor is between 0.000007 and 0.000021 (0.0007 – 0.0021%). Only a certain fraction of this material

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[6] In reality the national legislation actually contained two limits a 5 mg/m³ limit if the total emission from the plant remain exceed 200 g/h and a 20 mg/m³ limit if the total emissions remain below 200 g/h. Theoretically, the service provider could have argued that the plant was still within the national limits.

will be PVC or (micro)plastics in general, given that input material contains other materials as well. As such the release of microplastics from Plant D is strictly limited.

What this data also shows is that there are countries which set limits on total channelled dust emissions of plastics recycling companies. In this case the limit was 5 mg/m^3 per stack if total emissions exceed 200 g/h or 20 mg/m^3 per stack if total emissions remain below 200 g/h. If all stacks were emitting air with the maximum concentration of 5 mg/m^3 then the total emissions would have been 172 g/h. This would still result in a rather limited emission factor of 0.000057 - 0.000172 (0.0057 – 0.0172%). It is unlikely that there are EU countries that do not have similar legislation on dust emissions from plastics recycling facilities. Thus, there are legal limits in the EU that mean that channelled emission factors from plastics recycling facilities may not be greater than 0.02%.

Diffuse emissions

In Plant D, all waste material is stored in bunkers that are designed to prevent fire spread but have since been augmented with additional barriers (fences/nets) to prevent spread of (micro)plastic material (see Figure 35). Care is also taken by the operator of the plant to prevent overfilling of the bunkers. This has an added benefit of preventing the mixing of waste material streams which would render the recycling more complicated.

In terms of wastewater emissions, plant D processes all rain and wastewater on site and has no connection to emit wastewater to an urban wastewater treatment plant.

All in all, the plant understands that the release of (micro)plastics to the environment is something to prevent and has taken measures to limit this.

Figure 35 One of the smaller bunkers of Plant D with a batch of post-consumer industrial pipes. Note the fencing/netting installed on top of the bunker wall.

CONCLUSIONS

Workplace exposure

Dust

Measurements revealed that airborne concentrations of dust tend to be well below the limit used as reference in this report (5 mg/m³ for inhalable and 1 mg/m³ for respirable dust). The sole exception was one worker in an extrusion role which worked in an environment with 30.6 mg/m³ inhalable dust (and 0.45 mg/m³ respirable dust). This operator wore a full mask respirator with particle filter. In an overview of nominal and assigned protection factors compiled for this report (Table 3) one can see that the NPF for this type of mask varies between 4 and 48 while the assigned protection factors vary between 4 and 30. There seems to be agreement that for the P2 type filter version, the protection factor should be 10. As such the calculated personal exposure of this worker is 3.1 mg/m³ inhalable (And 0.05 mg/m³ respirable) dust, and well within the limit set by this report.

Calculated summary statistics for inhalable and respirable exposure in rigid PVC recycling facilities can be found in Table 26.

Table 26 Summary Statistics for Inhalable and Respirable Dust Exposure (in mg/m³) in Rigid PVC Recycling Facilities. An assigned protection factor of 10 was used for those measurements where RPE is worn. For datapoints where exposure was below the limit of detection, the limit of detection was used to calculate the summary statistics.

	Inhalable	Respirable
n	19	19
25th Percentile	0.3	0.08
Median	0.4	0.09
75th Percentile	0.7	0.12
90th Percentile	1.3	0.15

In future, this data can be used to make reasonable worst-case estimates of exposure to substances used in rigid PVC. Not by using the figures itself as estimates (that would be unreasonable worst case), but by assuming a certain additive use rate. For example, if “Substance X” was used in window profile formulations at a rate of at most 1% and there is an estimate that it was used in 20 – 30% of profiles historically, then one can calculate a reasonable worst case estimate for workplace exposure in construction profile recycling plants based on the 90th percentile for inhalable dust: 1.3 [mg/m³] x 0.01 x 0.30 = 0.0039 mg/m³ (or 3.9 µg/m³).

Since rigid PVC tends to be a quite rigid material amongst the family of rigid plastics (PP, PS, ABS), the data could be a good proxy for exposure that may be expected to occur in other rigid plastics recycling facilities as well.

Lead and Cadmium

In all but one case was the airborne concentration of lead and cadmium well below the occupational exposure limit of 30 and 1 µg/m³, respectively. The operator that was working in an airborne concentration of 80 and 6 µg/m³ of lead and cadmium, wore respiratory protective equipment with an assigned protection factor of at least 10 meaning that exposure was less than 8 and 0.6 µg/m³.

Table 27 Summary Statistics for Lead and Cadmium Exposure (in µg/m³) in Rigid PVC Recycling Facilities. An assigned protection factor of 10 was used for those measurements where RPE is worn. For datapoints where exposure was below the limit of detection, the limit of detection was used to calculate the summary statistics.

	Lead	Cadmium
n	19	19
25th Percentile	0.3	0.01
Median	0.7	0.02
75th Percentile	0.8	0.04
90th Percentile	1.1	0.23

Next to the airborne limit of 30 µg/m³, a biological limit value for lead has been established in the Carcinogens, Mutagens, and Reproductive Toxicants Directive (CMRD) of 30 µg Pb/100 ml blood until 31 December 2028 followed by a limit of 15 µg Pb/100 ml blood starting 1 January 2029. With some transitional provisions that indicate that if limits are exceeded, but a downward trend exits workers may continue to work.

Furthermore, the CMRD indicates that if airborne exposure is greater than 0.015 mg/m³ [=15 µg/m³] or lead blood levels are greater than 9 µg Pb/100 ml blood there should be medical surveillance of the workers. For female workers of childbearing age there is an additional limit of 4.5 µg Pb/100 ml blood above which medical surveillance is required.

In a 2016 study performed by the Vinyl Recycling Consortium, an ad-hoc consortium of recycling and downstream converting companies managed by Polymer Comply Europe, together with Dr. Claudia Fruijtier-Pölloth ERT of CATS Consulting GmbH (Fruijtier-Pölloth 2016), whole blood measurements were performed in 127 workers in the PVC recycling and converting value chain. The results showed that for the 100 workers for which individual results were available that the lead blood levels were 4.4 µg Pb/100 ml blood on average with a range of 0.8 – 13.0 µg Pb/100 ml blood and a 90th percentile of 8.8. This data indicates that already in 2016, the lead blood limits of 2029 were not exceeded in the PVC recycling value chain.

Whether or not medical surveillance will need to be performed by PVC recycling facilities will depend entirely on the lead blood levels of their workers since the 15 µg/m³ airborne exposure trigger limit is not breached. It is likely that quite a few plants have a workforce where the blood lead level remains below 9 µg Pb/100 ml blood and below 4.5 µg Pb/100 ml blood in female employees of childbearing age.

Furthermore, any lead (and cadmium) present in PVC powder would have limited biological availability. A large fraction of the inhaled dust will have a particle size distribution that is deposited in the upper respiratory tract from which it is cleared by mucociliary clearance and subsequently ingested (Antunes and Cohen 2007). The release of substances from a polymer matrix has been extensively investigated (Schwope 1990; Piringer and Baner 2008) and will limit release of the lead ions as the dust passes the gastrointestinal tract. Only the respirable fraction of the dust, which deposits in the lower respiratory tract and is thus not subject to mucociliary clearance should be expected to be absorbed completely. As the exposure levels to respirable dust are limited in rigid PVC recycling, it is questionable whether the lead in PVC dust exposure will meaningfully contribute to lead blood levels.

Organotins

As explained in the methods section on Organotins, only tin was measured in the inhalable dust fraction. This value (or the limit of detection in most cases) was used to calculate maximum concentrations of different organotin substances assuming that all tin measured is caused by the individual organotin. In reality, if tin is detected, it will likely be due to the presence of various species of (organo)tins that have been used in PVC and potentially other sources of tin in the airborne dust. As such it is an inherently conservative worst-case approach.

The conservativeness of the approach is compounded by the fact that phase out of the substance with the lowest DNEL DOTE in favour of MOTE and other organotin species, has been underway for decades. Furthermore, in B&C applications historically there has been greater reliance on methyl tin stabilisers. As such any conclusions based on maximum DOTE concentrations should be considered extreme worst-case.

The approach is however much more practical. Quantifying organotin in the inhalable fraction directly is much more laborious, analytically difficult, associated with greater error margins, and greater cost than quantification of tin by ICP-MS. Furthermore, by using ICP-MS a range of other elements can be quantified at little to no additional laboratory effort and thus cost. This enables simultaneous investigation into lead and cadmium OEL compliance for example.

There is however a downside to the use of this method. If results would have shown that the calculated maximum concentration of an organotin is above its threshold, further investigation would need to be performed to determine the actual level of organotin as one cannot conclude that the plant is in non-compliance based on the maximum organotin concentration alone. Such further investigation could be done by either:

1. performing another inhalation exposure measurement campaign with a filter for inhalable dust and sending the filter for organotin quantification, or
2. taking a sample of recyclate and sending this for organotin quantification to establish the ratio of the different organotins in the recyclate and recalculating the organotin concentration in the indoor dust based on this ratio.

The second option would be considerably more economical since it would be one analysis instead of several. Furthermore, from an analytical chemistry perspective, it tends to be easier and much more precise to quantify a concentration in a larger quantity of sample (e.g. 10 grams of recyclate) than in a smaller quantity (e.g. 0.3 mg of inhalable dust on a glass fibre filter).

There is of course a third alternative path for such hypothetical cases where the maximum organotin concentrations exceed the limit values. One could implement more risk management measures to reduce the exposure to tin to reduce the calculated maximum organotin exposure.

Regardless, the summary statistics for measured tin exposure and calculated maximum organotin exposure in rigid PVC recycling facilities can be found in Table 28.

Table 28 Summary Statistics for Tin Exposure (in µg/m³) and calculated maximum organotin concentrations in Rigid PVC Recycling Facilities (highlighted for clarity; see text for explanation). An assigned protection factor of 10 was used for those measurements where RPE is worn. For datapoints where exposure was below the limit of detection, the limit of detection was used to calculate the summary statistics.

	Sn	Max DOTE	Max DMTE	Max MMTE
n	19			
25th Percentile	0.07	0.4	0.3	0.4
Median	0.12	0.8	0.6	0.8
75th Percentile	0.20	1.3	0.9	1.3
90th Percentile	0.46	2.9	2.2	2.9

When the 90th percentile concentrations of DOTE, DMTE, and MMTE of 2.9, 2.2, and 2.9 µg/m^3 are compared to the DNELs used in the ECHA investigation report of 25, 180, and 5750 µg/m^3 in can be concluded that workers in rigid PVC recycling are operating safely.

It should however be noted that there is uncertainty with regards to the toxicological properties of the organotin substances. For example, it used to be understood that dialkyl bis-alkylthio esters would degrade to a dialkyl dichloride metabolites. Toxicological studies of dialkyl dichlorides have indicated reproductive toxicant properties and thus it was presumed that the dialkyl bis-alkylthio esters would be reproductive toxicants as well. It is the basis for their harmonised classification (and thus in some case SVHC identification).

New evidence however suggests that dialkyl bis-alkylthio esters do not metabolise to dialkyl dichloride and new reproductive toxicity studies of DOTE, DBTE, DMTE show no developmental toxicity (Costlow et al. 2021; Kirf et al. 2023; Costlow, Nasshan, and Frenkel 2017). These studies do however show a common maternal toxicity effect in the thymus of the experimental animals for which the rabbit seems to be less susceptible than rats and mice. It is possible that such findings can impact further investigation into an occupational exposure limit currently being conducted by the European Chemicals Agency may result in new insights that could result in new occupational exposure limits that may be higher or lower than the currently used DNELs.

Antimony, Zinc, Titanium, and Calcium

As explained in the individual plant chapters, exposure to antimony and zinc is controlled to below their respective limit values. No risk assessment is performed for titanium and calcium given the relatively limited toxicological hazard of these potential associated molecules (i.e. titanium dioxide, calcium carbonate, and calcium fatty acid salts). Summary statistics for exposure to these elements can be found in Table 29.

Table 29 Summary Statistics for Antimony, Zinc, Titanium and Calcium Exposure (in µg/m^3) in Rigid PVC Recycling Facilities. An assigned protection factor of 10 was used for those measurements where RPE is worn. For datapoints where exposure was below the limit of detection, the limit of detection was used to calculate the summary statistics.

	Antimony	Zinc	Titanium	Calcium
n	19	19	19	19
25th Percentile	0.01	1.50	0.35	16
Median	0.03	2.62	0.45	21
75th Percentile	0.20	6.22	0.65	28
90th Percentile	0.27	10.74	0.78	36

Of some note here is that antimony was found in 13 inhalable dust samples. As alluded to in the Antimony, Calcium, Zinc, and Titanium section of the methods chapter, antimony was included for its potential presence due to the use of antimony trioxide (ATO) as a synergist to the halogenated flame retardant action of the chlorine of the PVC polymer. Normally there is no need to use ATO in rigid PVC formulations, since rigid PVC is self-extinguishing[7] and it is thus some may find it surprising to find antimony in so many of the inhalable dust samples. However, the average concentration of antimony in the dust was just 0.023% (233 mg/kg) and there can be other sources of antimony. For example, household dust in general has an antimony concentration of around 26 mg/kg (Oomen et al. 2008). Perhaps it is used in rubber as well as a synergist to halogenated flame retardants. In any case, with such low concentrations in the dust, it is unlikely that there is a large previously unreported use of ATO in rigid PVC formulations.

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[7] ATO use is limited to some specific flexible PVC formulations as the addition of normal plasticiser dilutes the chlorine content and therefore decreases the inherent flame retardancy. Furthermore, in most flexible PVC applications flame retardancy is not needed and ATO is not used.

Environmental Emissions

The ECHA investigation report on PVC and its additives stated that: "*end-of-life (recycling and landfills) can be considered the main contributor to the overall releases of prioritised PVC additives.*". Figure 5 of the report indicates that 28.5% of all emissions are caused by recycling (while the accompanying text indicates the recycling accounts for ~31% of releases).

To understand how this relatively large fraction is attributed to recycling, table 52 of the appendix A+B of the report provides clarity. For conventional life cycle stages, refined release factors from the OECD Emission Scenario Document for Plastics Additives (OECD 2014) are available and used. However, for the professional and waste stages generic, thus conservative, factors from ECHA guidance R16 (ECHA 2016) and R18 (ECHA 2012) are used, respectively (Table 30). For recycling, an emission factor of 10% to air is applied, although this assumption has been questioned by the thermoplastics recyclers based on their practical experience.

*Table 30 Emission factors used in the ECHA Investigation Report, their methodological basis, and a heatmap of total emission factor used. Based on: ECHA Investigation Report Appendix A+B Table 52. * R16 was used to establish a release factor for soil, which is not done in the OECD ESD.*

Exposure Scenario	Estimation Method	Water	Air	Soil	Total
ES1: Formulation (PVC compounding)	OECD	0.08%	0.03%	0%	0.1%
ES2: Article production (PVC conversion)	OECD	0.25%	0.25%	0%	0.5%
ES3: Article service life. Use in pipes and pipe fittings	OECD | R16*	3.20%	0.05%	1.60%	4.9%
ES4: Article service life. Use in window frames	OECD | R16*	1.60%	0.05%	1.60%	3.3%
ES5: Article service life. Use in cables	OECD	0.05%	0.05%	0%	0.1%
ES6: Article service life. Use in flooring	OECD | R16*	1.60%	0.05%	1.60%	3.3%
ES7: Article service life. Use in packaging)	OECD | R16*	1.60%	0.05%	1.60%	3.3%
ES8: Article service life. Use in toys	OECD | R16*	1.60%	0.05%	1.60%	3.3%
ES9: Article service life. Use in artificial leather	OECD | R16*	1.60%	0.05%	1.60%	3.3%
ES10: Article service life. Automotive interiors	OECD | R16*	1.60%	0.05%	1.60%	3.3%
ES11: Article service life. Medical application	OECD	0.05%	0.05%	0.00%	0.1%
ES12: Professional use. Handling plastic articles	R16	2.50%	2.50%	2.50%	7.5%
ES13: Waste stage. Recycling	R18	0.00%	10%	0.00%	10.0%
ES14: Waste stage. Landfill	R18	1.60%	0.05%	3.20%	4.9%
ES15: Waste stage. Incineration	R18	0.01%	0.01%	0.00%	0.0%

The ECHA Guidance R18 contains a table R18-6 which forms the basis for this 10% to air estimate (reproduced for clarity in Figure 36), which clarifies that this factor is based on "expert judgment". The footnote 68 on this expert judgement on this states that: "*In this guidance expert judgement has been used as source to derive default values when necessary due to lack of basic data in literature. Experience and sector knowledge have been used to derive default values when available information does not allow to correlate emissions of single substances to the amount of that substance entered into a waste treatment process.*". In other words, an emission factor was necessary, no data was available, and the emission factor was established using expert judgement and the best available technical assumptions. However, some logic went into the estimates (e.g. what can be expected to be a dusty process or not) and there is great transparency on the strength of evidence behind the factors.

On the logic of the release estimates themselves, it should be noted that the propensity of a material to generate dust is mostly related to its brittleness/flexibility. In this report, it is shown that construction profile recyclers utilise this property to separate materials[8]. From this perspective, grouping plastics with minerals is somewhat inappropriate as minerals would in a shredding process generate far more dust. The lower factor for rubber versus plastics however is appropriate from this perspective, however the higher factor versus metal is entirely inappropriate. On paper, it should be noted that moisture content would very much impact the propensity of the material to generate dust. Shredding dry paper would likely result in great dust generation than the shredding of plastics, and the shredding of wet paper would likely result in less dust generation than the shedding of plastics. The wetness of plastics also has a somewhat similar effect, though to a much lesser extent.

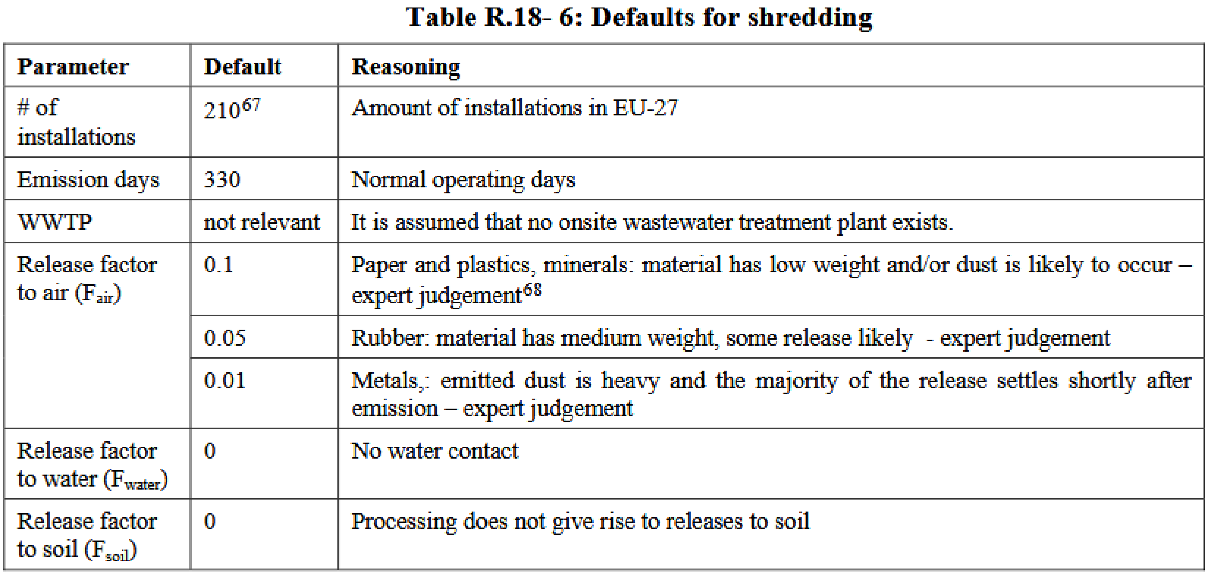

Table R.18- 6: Defaults for shredding

Parameter	**Default**	**Reasoning**
# of installations	210[67]	Amount of installations in EU-27
Emission days	330	Normal operating days
WWTP	not relevant	It is assumed that no onsite wastewater treatment plant exists.
Release factor to air (F_{air})	0.1	Paper and plastics, minerals: material has low weight and/or dust is likely to occur – expert judgement[68]
	0.05	Rubber: material has medium weight, some release likely - expert judgement
	0.01	Metals,: emitted dust is heavy and the majority of the release settles shortly after emission – expert judgement
Release factor to water (F_{water})	0	No water contact
Release factor to soil (F_{soil})	0	Processing does not give rise to releases to soil

Figure 36 Table R.18-6 as included in ECHA Guidance R.18

Then the "heaviness" of the generated dust in the logic of the guidance also deserves a closer look. In reality, it would be better to look at "density" of the dust (or even the weight to surface ratio of the generated dust). It is true that the density of metals is far greater than the other materials (e.g. iron 7.9 g/cm^3). However, minerals (e.g. calcium oxide 3.34 g/cm^3) have an intermediate density compared to paper (e.g. common printing paper 0.8 g/cm^3), plastics (e.g. PE 0.87 – 0.97 and PVC 1.3 – 1.45 g/cm^3), and rubber (0.92 – 1.5 g/cm^3).

The density of the material is however imperfect and only a proxy for the property of weight to surface ratio that determines to a greater degree the propensity of dust to fly off in the wind. A very fine metal dust would fly further than a lump of paper. It is for this reason that the dust generated from the shredding of dry mineral waste may have a greater emission potential than that of plastics for example, as more and finer particles would be created.

Taking the above into account, the propensity for material to emit dust from shredding would follow the following logic: minerals > dry paper > plastics and wet paper > metal > rubber.

Then there is the height of the factor that should be evaluated. In the OECD ESD there are no factors for shredding, but there is some development on grinding. For example, in paragraph 83: "*Wherever possible, internally generated scrap/waste is reground and reused on site in the conversion process. The regrinding process does generate some waste but this is in the form of large particles which are landfilled. Where*

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[8] Following shredding, glass has shattered into tiny pieces, rubbers tend to remain largely unaffected, and PVC profiles get an intermediate size; allowing for first separation by sieving.

regrinding is not possible, the scrap appears as industry waste and is usually landfilled. There are a few instances where scrap plastics materials are used on site as a fuel but this is very rare." Furthermore, in the chapter on fillers subsection on conversion it is stated that: "*One potentially significant source of emission is grinding where, for example, some thermosetting composites may be reshaped after cure. The waste grindings, which are very likely to be fragments of filler bound to plastic, are usually taken off into local exhaust ventilation (LEV). The worst-case scenario is where the filler is fully released, i.e. as a mixed dust in proportions representative of the original filler loading. Such losses may be significant, but seem unlikely to exceed 2.5% of filler.*" In several places in the document, it is assumed that material going through a grinding process a total of 2.5% would be emitted, partially to water partially to waste.

When evaluating this factor, it should be noted that the first edition of this ESD was created in 2009 and was associated with the "conversion" chapters of the different additive classes. As such, it was probably a factor based on relatively **small-scale indoor** grinding operations that many converters had and maintain to this day to simply reduce the size of off cuts to millimetre scale and feed the resulting regrind back into the original production process. To get an understanding of the scale of such processes, a back of envelope calculation might be warranted. Roughly 50 million tons of plastics are consumed in the EU, by around 50 000 companies. Assuming all use an equal amount, they convert 1000 tons per company. Companies would optimise their production process to have as little off-cuts as possible and a scrap rate of 2-5% would already be large. The amount of material being ground per company would be in the order of 20 – 50 tons. With such volumes, one would not expect the greatest containment and risk management measures to be in place. It would not be odd to expect the area around such a piece of equipment to be surrounded by debris and dust which would then be cleaned periodically by sweeping and vacuum cleaning (the part of the 2.5% emitted fraction that goes to waste) potentially followed by mopping (the part of the 2.5% emitted fraction that goes to water).

Grinding also occurs within the rigid PVC recycling facilities, and this is also normally done indoor. However, the scale at which it occurs is substantially different. Following separation of many non-PVC materials to a state that the material is primarily composed of PVC (and rubber) the shredded material is ground. In all plant descriptions it can be read that the grinding is done indoors, and all grinders are very much enclosed and equipped with extraction ventilation that removes dust to the dedicated air cleaning systems. This means that while 2.5% of dust may be generated, the emissions from grinding are controlled and under the channelled emission controls. Channelled environmental emissions were at the level of 0.0007 – 0.0021 % or 7 - 21 g dust/ton of PVC waste processed and as such are an extremely minor source of environmental release of microplastics.

What remains is to estimate the release from the shredding operation that in all investigated plants occurs outside. In this regard, it is not unreasonable to assume that the shredding process that is designed to reduce the size of the PVC material to the centimetre scale would generate 10 times less dust than the grinding process which is designed to reduce the PVC material to the millimetre scale. Given this logic, the total generated potential emissions would be 0.25%. This would still likely be a grand overestimation of reality as it would imply a release of 2.5 kg / ton of material shredded. For shredding other methodology based on BUBE-Online for example comes to a factor of 5 – 25 gram / ton of material shredded (Technical support for BUBE-Online: Corporate environmental data reporting, emission spectra and emission factors for the calculation of emissions according to the 11th Federal Immission Control Ordinance (BImSchV) of the Federal/State Cooperation VKoopUIS "Electronic PRTR Recording and Reporting System" (ePRTR), Version 1.0 (05/2009) [Fachhilfe für BUBE-Online: Betriebliche Umweltdatenberichterstattung Emissionsspektren und Emissionsfaktoren für die Berechnung von Emissionen 11. BImSchV der Bund-/Länder Kooperation VKoopUIS „Elektronisches PRTR-Erfassungsund Berichtsystem“ (ePRTR), Version 1.0 (05/2009)]).

Finally, the distribution to different environmental compartments should be considered. The model provided by Plant B on the deposition of dust from their facility shows that the vast majority of generated dust deposits on the site itself and only minimal amounts are deposited in adjacent areas. Given the impermeable surface common in recycling facilities, only the faction that deposits outside of the site premises would be emission to soil. As such, the fraction of the 0.25% that are released to air and soil should be expected to be rather minor; perhaps 0.01% each[9].

Of the remaining 0.23% it is likely that the street cleaning cars, widespread sweeping practices, and other less quantifiable techniques will capture a substantial fraction of this material into the waste output of the plant. Furthermore, physical filters/screens in the rainwater drainage systems also redirect some of the emissions that would otherwise go to water to a waste fraction. From this perspective it would be reasonable to assume that 0.2% goes to waste and 0.03% goes to water in PVC recycling facilities.

*Table 31 Environmental Emission Factors for Rigid PVC Recycling Facilities. * Worst-case based on expert judgement described above.*

	Air	Soil	Water	Waste
Shredding*	0.01%	0.01%	0.03%	0.2%
All subsequent recycling operations (under channelled emission control)	0.0007-0.0021%	0%	0%	

REFERENCES

ANSES. 2020. *Valeurs limites d'exposition en milieu professionnel: Le dioxyde de titane sous forme nanométrique.* https://www.anses.fr/fr/system/files/VSR2019SA0109Ra.pdf.

Antunes, Marcelo B., and Noam A. Cohen. 2007. "Mucociliary clearance – a critical upper airway host defense mechanism and methods of assessment." *Current Opinion in Allergy and Clinical Immunology* 7 (1). https://journals.lww.com/co-allergy/fulltext/2007/02000/mucociliary_clearance___a_critical_upper_airway.3.aspx.

Auer, Gerhard, Peter Woditsch, Axel Westerhaus, Jürgen Kischkewitz, Wolf-dieter Griebler, Markus Rohe, and Marcel Liedekerke. 2017. "Pigments, Inorganic, 2. White Pigments." In *Ullmann's Encyclopedia of Industrial Chemistry*, 1-36.

BUBE. *Technical support for BUBE-Online: Corporate environmental data reporting, emission spectra and emission factors for the calculation of emissions according to the 11th Federal Immission Control Ordinance (BImSchV) of the Federal/State Cooperation VKoopUIS "Electronic PRTR Recording and Reporting System" (ePRTR), Version 1.0 (05/2009) [Fachhilfe für BUBE-Online: Betriebliche Umweltdatenberichterstattung Emissionsspektren und Emissionsfaktoren für die Berechnung von Emissionen 11. BImSchV der Bund-/Länder Kooperation VKoopUIS „Elektronisches PRTR-Erfassungsund Berichtsystem" (ePRTR), Version 1.0 (05/2009)].*

Costlow, Richard D., Hans Nasshan, and Peter Frenkel. 2017. ""Simulated gastric hydrolysis and developmental toxicity of dioctyltin bis(2-Ethylhexylthioglycolate) [DOTE] in rabbits and mice"." *Regulatory Toxicology and Pharmacology* 87: 23-29. https://doi.org/https://doi.org/10.1016/j.yrtph.2017.03.026. https://www.sciencedirect.com/science/article/pii/S027323001730082X.

Costlow, Richard D., Hans Nasshan, Peter Frenkel, and Joseph Salsbury. 2021. "Simulated gastric hydrolysis and developmental toxicity of dibutyltin bis(2-ethylhexyl thioglycolate) in rats." *Journal of Applied*

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[9] It should be noted that deposition of 0.01% of the annual input to a PVC construction profile recycling facility in an area surrounding the plant would likely result in a clearly visible white coverage of this soil. As this was not the case for the plants investigated, it can be assumed that this is a rather conservative factor.

Toxicology 41 (11): 1794-1802. https://doi.org/https://doi.org/10.1002/jat.4162. https://doi.org/10.1002/jat.4162.

ECHA. 2012. *Guidance on information requirements and chemical safety assessment Chapter R.18: Exposure scenario building and environmental release estimation for the waste life stage.* https://echa.europa.eu/documents/10162/17224/r18_v2_final_en.pdf/e2d1b339-f7ca-4dba-8bdc-76e25b1c668c.

---. 2016. *Guidance on information requirements and Chemical Safety Assessment Chapter R.16: Environmental exposure assessment.* https://echa.europa.eu/documents/10162/17224/information_requirements_r16_en.pdf/.

---. 2023. *INVESTIGATION REPORT ON PVC AND PVC ADDITIVES.* (European Chemicals Agency). https://echa.europa.eu/completed-activities-on-restriction.

EN 529:2005 Respiratory protective devices - Recommendations for selection, use, care and maintenance - Guidance document.

Fruijtier-Pölloth, Claudia. 2016. *Health Risk of Occupational Lead (Pb) Exposure in Conventional PVC Recycling and Converting Operations.* (CATS Consultants GmbH).

Graf, Günter G. 2000. "Tin, Tin Alloys, and Tin Compounds." In *Ullmann's Encyclopedia of Industrial Chemistry*.

Heinrich, U., Fuhst R., Rittinghausen S., Creutzenberg O., Bellmann B., Koch W., and K. and Levsen. 1995. "Chronic Inhalation Exposure of Wistar Rats and two Different Strains of Mice to Diesel Engine Exhaust, Carbon Black, and Titanium Dioxide." *Inhalation Toxicology* 7 (4): 533-556. https://doi.org/10.3109/08958379509015211. https://doi.org/10.3109/08958379509015211.

INRS. 2019. *Les appareils de protection respiratoire: Choix et utilisation.* https://www.inrs.fr/media.html?refINRS=ED%206106.

Kirf, Dominik, Richard Costlow, Hans Nasshan, Peter Frenkel, and Donna Mondimore. 2023. "Simulated gastric hydrolysis and developmental toxicity of dimethyltin bis(2-ethylhexylthioglycolate) in rats." *Frontiers in Toxicology* Volume 5 - 2023. https://www.frontiersin.org/journals/toxicology/articles/10.3389/ftox.2023.1122323.

OECD. 2014. *Plastic Additives, Series on Emission Scenario Documents, No. 3.* (Paris: OECD Publishing). https://doi.org/10.1787/9789264221291-en.

Oomen, A.G., P.J.C.M. Janssen, A. Dusseldorp, and C.W. Noorlander. 2008. *Exposure to chemicals via house dust.* (RIVM). https://www.rivm.nl/bibliotheek/rapporten/609021064.pdf.

Piringer, Otto, and A.L. Baner. 2008. Plastic Packaging: Interactions with Food and Pharmaceuticals, 2nd, Completely Revised Edition.

RAC. 2017. Opinion proposing harmonised classification and labelling at EU level of Titanium dioxide. European Chemicals Agency.

Safety Guidelines for the Flexible Polyurethane Foam Industry. 2023. EUROPUR | EURO-MOULDERS. https://europur.org/wp-content/uploads/2023/09/Safety-Guidelines-2023-1.pdf.

Schiller, Michael. 2015. *PVC Additives Performance, Chemistry, Developments, and Sustainability*. Hanser Publications.

Schwab, Bruno, Andreas Ruh, Jens Manthey, and Marek Drosik. 2015. "Zinc." In *Ullmann's Encyclopedia of Industrial Chemistry*, 1-25.

Schwope, Arthur D.Goydan, Rosemary. 1990. Methods for Assessing Exposure to Chemical Substances. In *Methodology for Estimating the Migration of Additives and Impurities from Polymeric Materials*. Washington, D.C.: U.S. Environmental Protection Agency, Office of Toxic Substances.

SELECTIE EN GEBRUIK VAN ADEMHALINGSBESCHERMINGSMIDDELEN 2001. Nederlandse Vereniging voor Arbeidshygiëne. http://www.arbokennisnet.nl/images/dynamic/Dossiers/Machineveiligheid/D_Persoonlijke_beschermingsmiddelen.pdf.

Technical support for BUBE-Online: Corporate environmental data reporting, emission spectra and emission factors for the calculation of emissions according to the 11th Federal Immission Control Ordinance (BImSchV) of the Federal/State Cooperation VKoopUIS "Electronic PRTR Recording and Reporting System" (ePRTR), Version 1.0 (05/2009) [Fachhilfe für BUBE-Online: Betriebliche

Umweltdatenberichterstattung Emissionsspektren und Emissionsfaktoren für die Berechnung von Emissionen 11. BImSchV der Bund-/Länder Kooperation VKoopUIS „Elektronisches PRTR-Erfassungsund Berichtsystem“ (ePRTR), Version 1.0 (05/2009)].

Weil, Edward D., and Sergei V. Levchik. 2009. *Flame retardants for plastics and textiles : practical applications*. Cincinnati: Hanser Publishers.

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ANNEX I EXPOSURE MEASUREMENT RESULTS

*Table 32 Inhalable and respirable dust measurements. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red. * Operator wore appropriate tight fitting half mask respirator which will have awarded a protection factor of at least 10 indicating that the operator was working safely.*

ID	Sample Description	Time (min)	Inhalable Volume (l)	Inhalable Dust (mg)	Inhalable (mg/m^3)	Inhalable RCR	Respirable Volume (l)	Respirable Dust (mg)	Respirable (mg/m^3)	Respirable RCR
A1	JJ - Line Input Operator	161	322	0.14	0.43	0.09	356	<0.05	<0.14	<0.14
A2	TM - Sorting Line Operator	180	360	0.36	1.00	0.20	395	0.05	0.13	0.13
A3	SK - Extrusion Operator	205	410	0.19	0.46	0.09	451	<0.05	<0.11	<0.11
A4	FP - Lab Technician	203	407	0.17	0.42	0.08	446	0.08	0.18	0.18
B1	RS - Post Consumer (Outside)	401	847	0.37	0.44	0.09	888	0.08	0.09	0.09
B2	SP - Post Consumer (Outside)	406	855	0.3	0.35	0.07				
B3	JD - Post Consumer	347	731	0.48	0.66	0.13	766	0.07	0.09	0.09
B4	CC - Post Consumer	341	717	0.53	0.74	0.15	747	0.08	0.11	0.11
B5	SS - Pre Consumer	344	720	0.27	0.38	0.08	755	0.07	0.09	0.09
B6	BS - Electro-Static Sorting	370	779	0.55	0.71	0.14	810	0.25	0.31	0.31
B7	HS - Extrusion Operator	360	754	0.28	0.37	0.07	792	0.08	0.10	0.10
C1	Shredder Operator	292	587	0.18	0.31	0.06	642	<0.05	<0.08	<0.08
C2	Mechanical Sorting Operator	219	440	0.19	0.43	0.09	481	<0.05	<0.10	<0.1
C3	Electrostatic/Colour Sorting Operator	191	382	0.87	2.28	0.46	419	<0.05	<0.12	<0.12
C4	Extrusion Operator (Mask)*	202	405	12.4	30.62	0.61	446	0.20	0.45	0.05
D1	MoH - Outdoor Operator	291	582	0.1	0.17	0.03	640	<0.05	<0.08	<0.08
D2	RL - Mechanical Sorting Operator	276	552	0.19	0.34	0.07	607	<0.05	<0.08	<0.08
D3	KC - Micronisation Operator	332	664	0.15	0.23	0.05	730	<0.05	<0.07	<0.07
D4	RZ - Micronisation Operator	275	550	0.12	0.22	0.04	605	<0.05	<0.08	<0.08

*Table 33 Results of the tin in inhalable dust measurements and calculation of maximum organotin concentrations and Risk Characterisation Ratios (RCR) based on a limit of 25, 180, and 5750 $\mu g/m^3$ for DOTE, DMTE, and MMTE. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red. * Operator wore appropriate tight fitting half mask respirator which will have awarded a protection factor of at least 10 indicating that the operator was working safely.*

ID	Sample Description	Sn ($\mu g/m^3$)	Max DOTE ($\mu g/m^3$)	Max DMTE ($\mu g/m^3$)	Max MMTE ($\mu g/m^3$)	Max DOTE RCR	Max DMTE RCR	Max MMTE RCR
A1	JJ - Line Input Operator	<0.16	<0.98	<0.73	<0.97	<0.04	<0.004	<0.0002
A2	TM - Sorting Line Operator	<0.14	<0.88	<0.65	<0.87	<0.04	<0.004	<0.0002
A3	SK - Extrusion Operator	<0.12	<0.77	<0.57	<0.76	<0.03	<0.003	<0.0001
A4	FP - Lab Technician	<0.12	<0.78	<0.57	<0.77	<0.03	<0.003	<0.0001
B1	RS - Post Consumer (Outside)	<0.06	<0.37	<0.28	<0.37	<0.01	<0.002	<0.0001
B2	SP - Post Consumer (Outside)	<0.06	<0.37	<0.27	<0.37	<0.01	<0.002	<0.0001
B3	JD - Post Consumer	<0.07	<0.43	<0.32	<0.43	<0.02	<0.002	<0.0001
B4	CC - Post Consumer	<0.07	<0.44	<0.33	<0.44	<0.02	<0.002	<0.0001
B5	SS - Pre Consumer	<0.07	<0.44	<0.32	<0.44	<0.02	<0.002	<0.0001
B6	BS - Electro-Static Sorting	<0.06	<0.41	<0.3	<0.4	<0.02	<0.002	<0.0001
B7	HS - Extrusion Operator	<0.07	<0.42	<0.31	<0.42	<0.02	<0.002	<0.0001
C1	Shredder Operator	<0.17	<1.08	<0.8	<1.07	<0.04	<0.004	<0.0002
C2	Mechanical Sorting Operator	<0.23	<1.44	<1.06	<1.42	<0.06	<0.006	<0.0002
C3	Electrostatic/Colour Sorting Operator	<0.26	<1.66	<1.22	<1.64	<0.07	<0.007	<0.0003
C4	Extrusion Operator (Mask)*	0.679	4.300	3.177	4.254	0.017	0.002	0.0001
D1	MoH - Outdoor Operator	0.447	2.829	2.090	2.799	0.113	0.012	0.000
D2	RL - Mechanical Sorting Operator	1.178	7.457	5.509	7.377	0.298	0.031	0.001
D3	KC - Micronisation Operator	0.512	3.243	2.396	3.208	0.130	0.013	0.001
D4	RZ - Micronisation Operator	<0.09	<0.58	<0.43	<0.57	<0.02	<0.002	<0.0001

*Table 34 Airborne concentrations of lead (Pb), Cadmium (Cd), Antimony (Sb), Zinc (Zn), Titanium (Ti), and Calcium (Ca) as well as risk characterisation ratios for Pb, Cd, Sb, Zn, Ti, and Ca. RCR colour coding applied: <LOD = no shading, <0.1 = blue, 0.1 – 0.5 = green, 0.5 – 1.0 is yellow, and >1 = red. * Operator wore appropriate tight fitting half mask respirator which will have awarded a protection factor of at least 10 indicating that the operator was working safely.*

ID	Sample Description	Pb (µg/m^3)	RCR	Cd (µg/m^3)	RCR	Sb (µg/m^3)	RCR	Zn (µg/m^3)	RCR	Ti (µg/m^3)	Ca (µg/m^3)
A1	JJ - Line Input Operator	0.683	0.023	<0.016	<0.02	0.043	0.00017	9.63	0.019	<0.78	29.81
A2	TM - Sorting Line Operator	1.750	0.058	0.028	0.03	0.111	0.00044	11.94	0.024	<0.69	44.44
A3	SK - Extrusion Operator	0.129	0.004	<0.012	<0.01	0.341	0.00137	3.66	0.007	<0.61	13.66
A4	FP - Lab Technician	0.516	0.017	<0.012	<0.01	0.295	0.00118	7.13	0.014	<0.61	24.08
B1	RS - Post Consumer (Outside)	0.224	0.007	0.008	0.01	<0.01	<0.00004	2.48	0.005	<0.3	22.43
B2	SP - Post Consumer (Outside)	0.164	0.005	0.006	0.01	<0.01	<0.00004	1.52	0.003	<0.29	18.71
B3	JD - Post Consumer	0.766	0.026	0.033	0.03	0.008	0.00003	10.67	0.021	<0.34	35.57
B4	CC - Post Consumer	0.823	0.027	0.038	0.04	0.007	0.00003	11.02	0.022	<0.35	37.66
B5	SS - Pre Consumer	0.222	0.007	0.008	0.01	0.008	0.00003	2.50	0.005	<0.35	20.83
B6	BS - Electro-Static Sorting	0.706	0.024	0.033	0.03	0.027	0.00011	4.24	0.008	<0.32	33.38
B7	HS - Extrusion Operator	0.477	0.016	0.020	0.02	0.032	0.00013	5.31	0.011	<0.33	19.89
C1	Shredder Operator	<0.341	<0.011	<0.17	<0.17	<0.17	<0.00068	2.59	0.005	<0.51	11.45
C2	Mechanical Sorting Operator	0.980	0.033	<0.227	<0.23	<0.23	<0.00092	4.61	0.009	<0.68	26.57
C3	Electrostatic/Colour Sorting Operator	0.788	0.026	<0.262	<0.26	<0.26	<0.00104	<2.62	<0.005	<0.79	15.97
C4	Extrusion Operator (Mask)*	79.506	0.265	5.926	0.59	0.435	0.00017	14.81	0.003	43.01	201.36
D1	MoH - Outdoor Operator	0.070	0.002	<0.009	<0.01	0.010	0.00004	<0.86	<0.002	<0.43	6.01
D2	RL - Mechanical Sorting Operator	0.670	0.022	<0.009	<0.01	0.016	0.00006	1.03	0.002	<0.45	23.55
D3	KC - Micronisation Operator	0.934	0.031	<0.008	<0.01	<0.01	<0.00004	<0.75	<0.002	<0.38	16.57
D4	RZ - Micronisation Operator	0.424	0.014	<0.009	<0.01	0.236	0.00095	<0.91	<0.002	<0.45	12.18