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63/2026

Interim report

Concentrations of chlorine, PCDD/PCDF and dl-PCBs in ash from domestic wood-burning (small combustion plants) and medium-sized biomass combustion plants

by:
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On behalf of the Federal Environment Agency

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Kurzbeschreibung: Gehalte von Chlor, PCDD/PCDF und dl-PCB in Aschen aus privater Holzfeuerung (Kleinfeuerungsanlagen) und mittelgroßen BiomassefeuerungsanlageConcentrations of chlorine, PCDD/PCDF and dl-PCBs in ash from domestic wood-burning (small combustion plants) and medium-sized biomass combustion plants

PCDD/F und dl-PCB sind sogenannte „Persistente organische Schadstoffe“ (engl. Persistent organic pollutants; im Folgenden „POP“) und als solche, Gegenstand völkerrechtlicher Übereinkommen mit dem übergreifenden Ziel, Produktion, Verwendung und Freisetzung von POP so weit möglich zu reduzieren bzw. zu beenden. Die Umsetzung in der Europäischen Union erfolgt durch die Verordnung (EU) 2019/1021 vom 20. Juni 2019 (EU POP-Verordnung).

Da die dl-PCB toxikologische Eigenschaften haben, die denen von PCDD/F sehr ähnlich sind, wurden in der EU POP-Verordnung diese dioxinähnlichen Verbindungen in den bestehenden Gruppeneintrag für PCDD/F aufgenommen. Mit dieser Änderung wird für die PCDD/F und dl-PCB ein gemeinsamer Schwellenwert festgelegt, ab dem Abfälle nach Artikel 7 der EU POP-VO zu bewirtschaften und der POP-Gehalt zu zerstören ist (unterer POP-Grenzwert 5 µg/kg statt bisher 15 µg/kg). Die Mitgliedsstaaten sind aufgefordert, Daten über den Gehalt an PCDD/F sowie dl-PCB in Asche und Ruß aus privaten Haushalten sowie Flugasche aus Biomasseanlagen zur Wärme- und Stromerzeugung bis 1. Juli 2026 zu erheben.

Der vorliegende Bericht soll hierzu einen Beitrag aus deutscher Sicht liefern, sowie Grundlagen zur Beantwortung der Frage, ob eine weitere Absenkung des Grenzwertes unter Berücksichtigung des wissenschaftlichen und technischen Fortschritts machbar ist. Des Weiteren sollen die für Deutschland ermittelten Gehalte von PCDD/F und dl-PCB vor dem Hintergrund der abgesenkten Grenzwerte in der EU POP Verordnung für diese Verbindungen diskutiert werden.

Hierzu wurde eine Literaturrecherche durchgeführt und zur Erhebung von Daten zu Gehalten von PCDD/F und dl-PCB in Aschen von deutschen Kleinfeuerungsanlagen und mittelgroßen Biomassefeuerungsanlagen wurden Beprobungen an 20 Kleinfeuerungsanlagen sowie an 10 mittelgroßen Biomassefeuerungsanlagen vorgenommen.

Die Ergebnisse zeigen, dass die Grobaschen i.d.R. sehr niedrig belastet sind und Flugaschen grundsätzlich höhere Konzentrationen aufweisen, die jedoch in der Regel deutlich unterhalb bestehender regulatorischer Grenzwerte liegen. Hohe Konzentrationen, die in Einzelfällen im Bereich oder über den Grenzwerten liegen können, treten bei den beprobten Anlagen ausschließlich im Zusammenhang mit der Verbrennung von Altholz oder anderen be- oder verarbeiteten Hölzern auf. Der größte Anteil der Toxizität wird sowohl in der Grob- als auch in der Flugasche durch PCDD/F verursacht. Der Anteil der dl-PCB liegt in der Regel bei wenigen Prozentpunkten. Obwohl die Grobaschen in erheblich größeren Mengen anfallen, befindet sich bei Kleinfeuerungsanlagen etwa ¼ der gesamten TEQ-Fracht in den Grobaschen und ¾ in den Flugaschen.

Eine weitere Absenkung des Grenzwertes wäre möglich, sofern in den betreffenden Anlagen ausschließlich unbehandeltes oder nur mechanisch behandeltes Holz verbrannt wird.

Bei Anlagen, in denen Altholz der Kategorie A II oder andere, nicht nur mechanisch be- oder verarbeitete Hölzer verbrannt werden, können erhöhte PCDD/F und dl-PCB-Gehalte auftreten.

Es wäre zu prüfen, ob ein weiter gesenkter Grenzwert in solchen Fällen durch eine bessere Kontrolle des Brennstoffes einzuhalten ist. Eine Absenkung des Grenzwertes müsste dann mit entsprechenden Aufklärungsmaßnahmen einhergehen. Zusätzlich müssten in die Prüfung auch weitere PCDD/F und dl-PCB-Quellen mit einbezogen werden.

Abstract: Chlorine, PCDD/PCDF and dl-PCB content in ash from private wood-fired boilers (small combustion plants) and medium-sized biomass combustion plants

PCDD/Fs and dl-PCBs are persistent organic pollutants (POPs) and, as such, are subject to international agreements with the overarching goal of reducing or eliminating the production, use and release of POPs as far as possible. Implementation in the European Union is carried out by Regulation (EU) 2019/1021 of 20 June 2019 (EU POP Regulation).

Since dl-PCBs have toxicological properties very similar to those of PCDD/Fs, these dioxin-like compounds have been included in the existing group entry for PCDD/Fs in the EU POP Regulation. This adjustment establishes a common threshold for PCDD/Fs and dl-PCBs, above which waste must be managed in accordance with Article 7 of the EU POP Regulation and the POP content must be destroyed (lower POP limit 5 µg/kg instead of the previous 15 µg/kg). Member States should collect data on the content of PCDD/Fs and dl-PCBs in ash and soot from private households and fly ash from biomass units for heat and power production by 1 July 2026.

This report aims to contribute to this data collection from a German perspective and to provide a basis for answering the question of whether a further reduction of the limit value is feasible, taking into account scientific and technical progress. Furthermore, the levels of PCDD/Fs and dl-PCBs identified for Germany are to be discussed against the background of the reduced limit values in the EU POP Regulation for these compounds.

To this end, a literature review was conducted, and samples were taken from 20 small combustion plants and 10 medium-sized biomass combustion plants to collect data on PCDD/F and dl-PCB levels in ash from German small combustion plants and medium-sized biomass combustion plants.

The results show that coarse ash is generally very low in contamination and fly ash generally contains higher concentrations, but these are usually well below existing regulatory limits. High concentrations, which in individual cases may be at or above the limit values, occur at the sampled plants exclusively in connection with the combustion of waste wood or other processed wood. The largest proportion of toxicity in both coarse ash and fly ash is caused by PCDD/Fs. The proportion of dl-PCBs is usually a few percentage points. Although coarse ash is produced in considerably larger quantities, in small combustion plants approximately ¼ of the total TEQ load is found in coarse ash and ¾ in fly ash.

A further reduction in the limit value would be possible if only untreated or exclusively mechanically treated wood were burned in the plants concerned.

At plants that burn category A II waste wood or other wood that has not been treated or processed exclusively by mechanical means, elevated levels of PCDD/Fs and dl-PCBs may occur.

It would need to be examined whether a further reduction in the limit value can be achieved in such cases through better control of the fuel. A reduction of the limit value would then need to be accompanied by appropriate awareness-raising measures. In addition, other sources of PCDD/Fs and dl-PCBs would also need to be included in the assessment.

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List of abbreviations

Abbreviation	Explanation
BA	combustion chamber ash
BG	detection limit
BGA	Federal Health Office
BImSchV	Ordinance on the Implementation of the Federal Immission Control Act
BW	Baden-Württemberg
CA	coarse ash
CF	ceramic filter
Cl	chlorine
CLRTAP	Convention on Long-Range Transboundary Air Pollution
dl-PCB	dioxin-like polychlorinated biphenyls
DM	dry matter
EP	electrostatic precipitator
ERF	single-chamber combustion plant (in German: *Einzelraum Feuerungsanlagen*)
EU	European Union
FA	fly ash
FF	fabric filter
FWL	combustion heat output (in German: *Feuerungswärmeleistung*)
HHS	wood chips (in German: *Holzhackschnitzel*)
1,2,3,4,6,7,8-HpCDD	1,2,3,4,6,7,8-Heptachlorodibenzo-p-dioxin
1,2,3,4,6,7,8-HpCDF	1,2,3,4,6,7,8-Heptachlorodibenzofuran
1,2,3,4,7,8-HxCDD	1,2,3,4,7,8-Hexachlorodibenzo-p-dioxin
1,2,3,4,7,8-HxCDF	1,2,3,4,7,8-Hexachlorodibenzofuran
1,2,3,4,7,8,9-HpCDF	1,2,3,4,7,8,9-Heptachlorodibenzofuran
1,2,3,6,7,8-HxCDD	1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin
1,2,3,6,7,8-HxCDF	1,2,3,6,7,8-Hexachlorodibenzofuran
1,2,3,7,8,9-HxCDD	1,2,3,7,8,9-Hexachlorodibenzo-p-dioxin
1,2,3,7,8,9-HxCDF	1,2,3,7,8,9-Hexachlorodibenzofuran
2,3,4,6,7,8-HxCDF	2,3,4,6,7,8-Hexachlorodibenzofuran
HZH	wood-fired central heating (in German: *Holz Zentralheizung*)
I-TEQ	International Toxic Equivalents
N/A	not specified
kg	kilogram

Abbreviation	Explanation
kW	kilowatt
LAGA PN 98	LAGA Sampling Protocol 98 (Sampling protocol by the German Working Group on Waste – *Länderarbeitsgemeinschaft Abfall*)
mg	milligram
MW	megawatt
NA	not analysed
NATO	North Atlantic Treaty Organisation
NATO-CCMS	NATO Committee on the Challenges of Modern Society
ND	not detected
ng	nanogram
NWL	rated heat output (in German: *Nennwärmeleistung*)
OCDD	Octachlorodibenzo-p-dioxin
OCDF	Octachlorodibenzofuran
PCB	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzodioxins
PCDF	Polychlorinated dibenzofurans
1,2,3,7,8-PeCDD	1,2,3,7,8-Pentachlorodibenzo-p-dioxin
1,2,3,7,8-PeCDF	1,2,3,7,8-Pentachlorodibenzofuran
2,3,4,7,8-PeCDF	2,3,4,7,8-Pentachlorodibenzofuran
PCB 77	3,3',4,4'-tetrachlorobiphenyl
PCB 81	3,4,4',5-Tetrachlorobiphenyl
PCB 105	2,3,3',4,4'-pentachlorobiphenyl
PCB 114	2,3,4,4',5-pentachlorobiphenyl
PCB 118	2,3',4,4',5-Pentachlorobiphenyl
PCB 123	2',3,4,4',5-pentachlorobiphenyl
PCB 126	3,3',4,4',5-pentachlorobiphenyl
PCB 169	2,3,3',4,4',5-hexachlorobiphenyl
PCB 156	2,3,3',4,4',5'-hexachlorobiphenyl
PCB 157	2,3',4,4',5,5'-hexachlorobiphenyl
PCB 167	3,3',4,4',5,5'-hexachlorobiphenyl
PCB 189	2,3,3',4,4',5,5'-heptachlorobiphenyl
POP	Persistent organic pollutants
POP Regulation	Regulation (EU) 2019/1021 on persistent organic pollutants

Abbreviation	Explanation
PVC	Polyvinyl chloride
PM0.1	particulate matter ≤ 0.1 µm
PM1	particulate Matter ≤ 1 µm
PM2.5	particulate matter ≤ 2.5 µm
PM10	particulate matter ≤ 10 µm
RA	grate ash (in German: *Rostasche*)
RBA	grate ash + combustion chamber ash (in German: *Rostasche + Brennraumasche*)
SA	chimney ash (in German: *Schornsteinasche*)
SC	Stockholm Convention
SVA	ash from chimney and connecting pipe (in German: *Asche aus Schornstein und Verbindungsstück*)
TA	Technical Instructions (in German: *Technische Anleitung*)
TCDD	2,3,7,8-tetrachlorodibenzodioxin
2,3,7,8-TeCDD	2,3,7,8-tetrachlorodibenzodioxin
2,3,7,8-TeCDF	2,3,7,8-Tetrachlorodibenzofuran
TEF	Toxic Equivalency Factor
TEQ	Toxic Equivalent
TLLLR	Thuringian State Office for Agriculture and Rural Areas
TÜV SÜD	Technical Inspection Association of Southern Germany
UBA	Federal Environment Agency
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
VA	ash from connector (in German: *Asche aus Verbindugsstück*)
WHO	World Health Organisation
ZIV	Central Association of Chimney Sweeps

Zusammenfassung

Hintergrund und Zielsetzung

Der vorliegende Bericht befasst sich umfassend mit der Erhebung und Analyse von Daten zur Konzentration von polychlorierten Dibenzo-p-dioxinen und Dibenzofuranen (PCDD/F) und dioxinähnlichen polychlorierten Biphenylen (dl-PCB) in Grob- und Flugaschen aus privater Holzfeuerung (Kleinfeuerungsanlagen) und mittelgroßen Biomassefeuerungsanlagen in Deutschland.

PCDD/F und dl-PCB sind sogenannte „Persistente organische Schadstoffe" (engl. Persistent organic pollutants; im Folgenden „POP"), das sind bestimmte Stoffe, die giftig sind, langfristig in der Umwelt verbleiben und tausende von Kilometern von ihrem ursprünglichen Herstellungs- oder Verwendungsort entfernt auffindbar sind. Sie stellen eine langfristige Bedrohung für die menschliche Gesundheit und Ökosysteme dar.

POP sind Gegenstand völkerrechtlicher Übereinkommen mit dem übergreifenden Ziel, Produktion, Verwendung und Freisetzung von POP so weit möglich zu reduzieren bzw. zu beenden. Die Umsetzung in der Europäischen Union erfolgt durch die Verordnung (EU) 2019/1021 vom 20. Juni 2019 (EU POP-Verordnung). Diese regelt in Artikel 7 die Bewirtschaftung von Abfällen, die POP enthalten. Abfälle, die die in Anhang IV aufgeführten POP oberhalb festgelegter Grenzwerte enthalten, werden nach Art. 7 (2) so beseitigt oder verwertet, „[…] dass die darin enthaltenen POP zerstört oder unumkehrbar umgewandelt werden, damit die verbleibenden Abfälle und Freisetzungen nicht die Eigenschaften von POP aufweisen".

Da die dl-PCB toxikologische Eigenschaften haben, die denen von PCDD/F sehr ähnlich sind, und um die aggregierte Wirkung aller dl-PCB zu berücksichtigen, wurden in der EU POP-Verordnung diese dioxinähnlichen Verbindungen in den bestehenden Gruppeneintrag für PCDD/F aufgenommen. Mit der Änderung wird somit für die PCDD/F und dl-PCB ein gemeinsamer Schwellenwert festgelegt, ab dem Abfälle nach Artikel 7 der EU POP-VO zu bewirtschaften und der POP-Gehalt zu zerstören ist (unterer POP-Grenzwert 5 µg/kg[1] statt bisher 15 µg/kg).

Weiterhin sind die Mitgliedsstaaten aufgefordert, Daten über den Gehalt an PCDD/F sowie dl-PCB in Asche und Ruß aus privaten Haushalten sowie Flugasche aus Biomasseanlagen zur Wärme- und Stromerzeugung bis 1. Juli 2026 zu erheben.

Der vorliegende Bericht soll hierzu einen Beitrag aus deutscher Sicht liefern, sowie Grundlagen zur Beantwortung der Frage, ob eine weitere Absenkung des Grenzwertes unter Berücksichtigung des wissenschaftlichen und technischen Fortschritts machbar ist. Des Weiteren sollen die für Deutschland ermittelten Gehalte von PCDD/F und dl-PCB vor dem Hintergrund der abgesenkten Grenzwerte in der EU POP-Verordnung für diese Verbindungen diskutiert werden.

Ausgangssituation

Zur Betrachtung der Ausgangssituation wurde eine Recherche deutschsprachiger Literatur durchgeführt, um den Stand des Wissens zur Belastung von Grob- und Flugaschen aus deutschen Anlagen mit PCCD/F und dl-PCB und Zusammenhänge zwischen Schadstoffgehalt, Brennstoff und Art der Verbrennung darzustellen.

Im Fokus der Recherchen standen Kleinfeuerungsanlagen und mittelgroße Biofeuerungsanlagen in Deutschland.

Kleinfeuerungsanlagen sind Anlagen, die in der 1. BImSchV reguliert sind mit einer Feuerungswärmeleistung von weniger als 1 Megawatt (MW). Dabei werden

[1] 5 µg/kg = 5.000 ng/kg

Einzelraumfeuerungsanlagen und Festbrennstoffkessel unterschieden. Einzelraumfeuerungsanlagen sind Heizgeräte, die zur Beheizung einzelner Räume verwendet werden. Dazu gehören beispielsweise Kaminöfen, Kachelöfen, offene Kamine und Pelletöfen. In Deutschland gab es im Jahr 2023 rund 11,7 Millionen Einzelraumfeuerungsanlagen. Festbrennstoffkessel sind Heizkessel, die ebenfalls mit festen Brennstoffen (z. B. Holz, Pellets, Kohle) betrieben werden, aber speziell zur Beheizung eines gesamten Gebäudes ausgelegt sind. In Deutschland gab es im Jahr 2023 rund 1,13 Millionen Festbrennstoffkessel. Im Rahmen dieses Forschungsvorhabens wurden auch Betriebe der Holzbearbeitung oder Holzverarbeitung betrachtet, die bestimmte Brennstoffe einsetzen (bestimmtes gestrichenes, lackiertes oder beschichtetes Holz sowie daraus anfallende Reste bzw. Sperrholz, Spanplatten, Faserplatten oder sonst verleimtes Holz sowie daraus anfallende Reste), bei denen der Verdacht besteht, dass die Aschen möglicherweise relativ hoch mit PCDD/F und dl-PCB belastet sind.

Mittelgroße Biomassefeuerungsanlagen im Rahmen dieses Projekts sind Anlagen, die im Geltungsbereich der 44. BImSchV liegen. Dies sind Anlagen mit einer Feuerungswärmeleistung zwischen 1 und 50 Megawatt (MW) sowie genehmigungsbedürftige Feuerungsanlagen mit einer Feuerungswärmeleistung unter 1 MW. Nicht genehmigungsbedürftige Anlagen unter 1MW fallen unter die 1. BImSchV, während Anlagen mit einer Feuerungswärmeleistung von 50 MW oder mehr in der Regel in der 13. BImSchV geregelt sind. In Deutschland gibt es etwa 40.000 mittelgroße Feuerungsanlagen, davon ca. 800 Anlagen für feste Biomasse.

Bezüglich Einzelraumfeuerungsanlagen zeigt die Literaturrecherche, dass die PCDD/F-Gehalte je nach Art der Verbrennungsanlage, dem verwendeten Brennstoff und der Aschefraktion variieren. In Grobaschen aus Einzelraumfeuerungsanlagen sind die PCDD/F-Gehalte in der Regel relativ niedrig (<100 ng I-TEQ/kg). In der Flugasche sind die PCDD/F-Gehalte deutlich höher und können bis zu mehrere 1.000 ng I-TEQ/kg betragen. In einigen Studien wurden hohe Werte von über 10.000 ng I-TEQ/kg gemessen.

Bei Festbrennstoffkesseln hängen die PCDD/F-Gehalte in Aschen und Ruß von der Art des Brennstoffs und der Verbrennungstechnologie ab. In der Grobasche sind die PCDD/F-Gehalte in der Regel relativ niedrig (<100 ng I-TEQ/kg), insbesondere bei der Verbrennung von unbehandeltem Holz. Mit zunehmender Heizlast sinken die PCDD/F-Gehalte in der Asche. In der Flugasche sind die PCDD/F-Gehalte in der Regel moderat (<1.000 ng I-TEQ/kg). In Einzelfällen können die Gehalte auch über 1.000 ng I-TEQ/kg liegen. Bei der Verbrennung von anderen Biomassen als Holz, wie z. B. Stroh, sind teilweise höhere Werte zu finden, die sogar mehrere 1.000 ng I-TEQ/kg erreichen können.

Den Ergebnissen der Literaturrecherche zufolge, waren in Aschen, die bei holzverarbeitendem Gewerbe gewonnen wurden, die PCDD/F Gehalte der Grobasche sehr niedrig (< 1 ng/kg TEQ BGA), die der Flugasche niedrig (< 1.000 ng/kg TEQ BGA).

Die Aschen aus mittelgroßen Feuerungsanlagen sind der Literatur zufolge generell niedriger belastet als bei Kleinfeuerungsanlagen. Während Aschen aus der Verbrennung von unbehandelten Holzbrennstoffen niedrige Toxizitätswerte (<1 ng TEQ/kg) aufweisen, führt die Verbrennung von behandelten Hölzern zu höheren Werten.

Auswahl relevanter Anlagen, Probenahme und Analytik

Zur Erhebung von Daten zu Gehalten von PCDD/F und dl-PCB in Aschen von deutschen Kleinfeuerungsanlagen und mittelgroßen Biomassefeuerungsanlagen wurden Beprobungen an 20 Kleinfeuerungsanlagen sowie an 10 mittelgroßen Biomassefeuerungsanlagen durchgeführt.

Bei der Auswahl der 20 Kleinfeuerungsanlagen wurde darauf geachtet, dass diese eine möglichst breite und typische Auswahl des Anlagenbestands in Deutschland widerspiegeln. Insgesamt wurden 6 Einzelraumfeuerungsanlagen sowie 14 Festbrennstoffkessel aus verschiedenen Regionen Deutschlands beprobt.

Bei der Auswahl der mittelgroßen Biomassefeuerungsanlagen wurden anfangs Kriterien zur Auswahl der Anlagen für den gesamten Anlagenpark in Deutschland aufgestellt. Es wurden gezielt Anlagen einbezogen, bei denen mit höheren PCDD/F-Gehalten in den Aschen zu rechnen war, wie z. B. mit Altholz A II, Spanplatten oder Getreide als Brennstoff. Es wurden ausschließlich Flugaschen beprobt. Es handelt sich bei den ausgewählten Anlagen nicht um eine repräsentative Stichprobe.

Die Probenahmen erfolgten in Anlehnung an die LAGA PN 98 in der ersten Hälfte des Jahres 2025. Die Ascheproben wurden auf PCDD/F, dl-PCB und Gesamt-Chlor analysiert. Die Quantifizierung der PCDD/F und dl-PCB-Kongenere erfolgte mittels Gaschromatografie in Kopplung mit einem Tandem-Massenspektrometer (GC-MS/MS). Das durchführende Labor ist für die Bestimmung von POP wie PCDD/F und PCB gemäß DIN EN ISO/IEC 17025:2018 akkreditiert.

Auswertung der Ergebnisse

Die Ergebnisse der Laboranalysen werden im Bericht getrennt nach den Anlagenkategorien Kleinfeuerungsanlagen (Einzelraumfeuerungsanlagen, Festbrennstoffkessel, Kessel der holzbearbeitenden und holzverarbeitenden Betriebe) und mittelgroßen Feuerungsanlagen dokumentiert und graphisch dargestellt sowie im Zusammenhang mit den Details zu den beprobten Anlagen diskutiert.

Einzelraumfeuerungsanlagen

Es zeigt sich ein klarer Trend: Die Flugasche enthält deutlich höhere Konzentrationen von PCDD/F und dl-PCB als die Grobasche. Die gefundenen Konzentrationen variieren stark zwischen den Anlagen und lassen sich nicht eindeutig auf einzelne Einflussfaktoren wie Brennstoffart, Anlagenalter oder Bauweise zurückführen.

In der Grobasche waren die Konzentrationen von PCDD/F und dl-PCB überwiegend nicht nachweisbar. Unter Berücksichtigung der Bestimmungsgrenzen bewegt sich der berechnete gesamt-TEQ-Wert zwischen 1,05 und 1,12 ng TEQ/kg TS (WHO_{2005}). In der Flugasche wurden deutlich höhere Konzentrationen von PCDD/F und dl-PCB gemessen (max. 217 ng TEQ/kg TS (WHO_{2005})), die dennoch weiter unterhalb des Grenzwerts liegen.

Der weitaus größte Anteil der Toxizität (ausgedrückt als gesamt-TEQ) wird durch PCDD/F verursacht. Im Durchschnitt trugen die PCDD/F in den Flugaschenproben rund 97 % zum gesamt-TEQ bei, während der Anteil der dl-PCB bei etwa 3 % lag. Ein ähnliches Bild ergibt sich auch bei der Grobasche. Im Durchschnitt trugen die PCDD/F in den Grobascheproben rund 84 % zum gesamt-TEQ bei, während der Anteil der dl-PCB bei 16 % lag.

Festbrennstoffkessel

Wie bei den Einzelraumfeuerungsanlagen liegen die Konzentrationen von PCDD/F und dl-PCB in der Grobasche niedriger als in der Flugasche.

Die meisten Werte für Grobaschen liegen unterhalb ~2,5 ng TEQ/kg TS. Nur wenige Proben enthalten leicht erhöhte Konzentration von PCDD/F und dl-PCB (max. 100 ng TEQ/kg TS).

In der Flugasche wurden deutlich höhere gesamt-TEQ Konzentrationen gefunden. Bei den kleineren Kesseln bis 38 kW bis zu 372 ng TEQ/kg TS (PCDD/F & dl-PCB). Bei den größeren Kesseln ab 38 kW, besonders mit Bezug zum holzverarbeitenden Gewerbe, waren die TEQ-Werte auffällig hoch. Die höchsten gesamt-TEQ Konzentrationen (maximal 13.643 ng/kg TS (PCDD/F & dl-PCB)) wurden in den Flugaschen von Anlagen festgestellt, in denen Brennstoffe wie Spanplattenreste oder Holz aus dem holzverarbeitenden Gewerbe verfeuert wurden. Im Gegensatz dazu führten naturbelassene Hölzer als Brennstoff zu deutlich niedrigeren TEQ-Werten im Bereich von 1,75 bis 2,47 ng/kg TS.

Der weitaus größte Anteil der Toxizität wird durch PCDD/F verursacht. Im Durchschnitt trugen die PCDD/F in den Flugaschenproben rund 99 % zum gesamt-TEQ bei, während der Anteil der dl-PCB bei etwa 1 % lag. Bei der Grobasche trugen die PCDD/F in den Grobascheproben rund 97 % zum gesamt-TEQ bei, während der Anteil der dl-PCB bei 3 % lag.

Mittelgroße Feuerungsanlagen

Bei der Auswahl der Anlagen wurden gezielt Anlagen einbezogen, bei denen mit höheren PCDD/F- und dl-PCB-Gehalten in den Aschen zu rechnen ist. Erwartungsgemäß zeigen die ermittelten Konzentrationswerte der Flugaschen aus mittelgroßen Biomassefeuerungsanlagen daher insgesamt deutlich höhere Median- und Mittelwerte (119 bzw. 846 ng TEQ/kg TS; Maximalwert 5.230 ng TEQ/kg TS) als jene aus Kleinfeuerungsanlagen, mit Ausnahme der Flugaschen aus den Kesseln des Holzbe- und verarbeitenden Gewerbes.

Fazit

Grundsätzlich weisen die Ergebnisse darauf hin, dass die Grobaschen i.d.R. sehr niedrig belastet sind (max. 100 ng TEQ/kg TS) und Flugaschen grundsätzlich höhere Konzentrationen aufweisen, die in der Regel deutlich unterhalb bestehender regulatorischer Grenzwerte liegen. Hohe Konzentrationen, im Bereich von mehreren tausend ng TEQ/kg TS, treten bei den beprobten Anlagen ausschließlich im Zusammenhang mit der Verbrennung von Altholz oder anderen be- oder verarbeiteten Hölzern auf. Dort können in einzelnen Fällen auch PCDD/F und dl-PCB TEQ-Werte oberhalb des bestehenden Grenzwertes von 5.000 ng/kg TEQ vorkommen.

Der größte Anteil der Toxizität wird sowohl in der Grob- als auch in der Flugasche durch PCDD/F verursacht. Der Anteil der dl-PCB liegt in der Regel bei wenigen Prozentpunkten.

Schadstofffrachten

Zum Zweck der Auswertung und der Diskussion der Auswirkung einer möglichen Änderung des Anhang IV Grenzwertes für PCDD/F und dl-PCB der EU POP-Verordnung, wurden die in den Aschen aus den Kleinfeuerungsanlagen enthaltenen Schadstofffrachten ermittelt. Diese können durch Multiplikation der in den Aschen vorliegenden durchschnittlichen oder mittleren Konzentration mit den Aschemengen errechnet werden.

Die Berechnungen wurden für die Kleinfeuerungsanlagen, getrennt nach Anlagentyp, für Einzelraumfeuerungsanlagen, Festbrennstoffkessel sowie für die Kessel der holzbe- und verarbeitenden Betriebe sowie getrennt für Grob- und Flugasche durchgeführt.

Bezüglich der mittelgroßen Feuerungsanlagen ist eine Abschätzung der Frachten an PCDD/F und dl-PCB auf Grundlage der vorliegenden Daten aus verschiedenen Gründen nicht sinnvoll möglich.

In Summe liegen die jährlichen gesamt-TEQ-Frachten für PCDD/F und dl-PCB in Aschen aus den betrachteten Kleinfeuerungsanlagen im niedrigen einstelligen Grammbereich. Der weitaus überwiegende Anteil der TEQ-Fracht stammt sowohl in der Grobasche als auch in der Flugasche aus der PCDD/F Belastung. Den im Bericht angestellten Schätzungen zufolge betragen die Frachten in den Grobaschen (Aschemenge ~129 kt) insgesamt ca. 0,6 g und in den Feinaschen (Aschemenge ~8,7 kt) ca. 1,8 g (jeweils basierend auf Mittelwerten). Daraus lässt sich auch schließen, dass etwa ¼ der gesamt-TEQ Fracht in den Grobaschen und ¾ in den Flugaschen enthalten ist.

Vergleich der Ergebnisse mit Literaturangaben

Ein Vergleich der in diesem Vorhaben gemessenen PCDD/F und dl-PCB-Konzentrationen in Grob- und Flugasche mit Werten aus der Fachliteratur für Deutschland zeigt, dass die Ergebnisse der im Rahmen dieses Projekts durchgeführten Untersuchungen grundsätzlich mit den Informationen aus der Literaturstudien übereinstimmen, auch wenn sie im Einzelnen abweichen können.

In einem weiteren Vergleich wurden die gemessenen mit entsprechenden Werten aus anderen europäischen Ländern verglichen. Insgesamt zeigen die Ergebnisse, dass die Gehalte in Deutschland im Rahmen der aus anderen Ländern berichteten Werte liegen. Rußproben aus Kaminen kleiner Holzfeuerungsanlagen zeigen deutlich, dass die Belastung mit PCDD/F stark vom eingesetzten Brennstoff abhängt. Bei der Verbrennung von naturbelassenem Holz und etwa Papier zum Anzünden sind die PCDD/F Konzentrationen relativ gering. Sobald jedoch behandelte oder verunreinigte Hölzer, Kunststoffe, Alufolie, Karton oder Haushaltabfälle mitverbrannt werden, steigen die gemessenen Werte stark an. Dies erklärt teilweise die hohen PCDD/F Werte, die in der Literatur aus anderen Ländern berichtet werden.

In diesem Vorhaben wurden bei mittelgroßen Feuerungsanlagen Werte gemessen, die teilweise um mehrere Größenordnungen über denen liegen, die für Holzverbrennung in der untersuchten Literatur berichtet wurden. Daraus lässt sich allerdings nicht schließen, dass die Belastung dieser Aschen in Deutschland höher wäre als in den anderen betrachteten Ländern. Der Grund für die in Deutschland vergleichsweise hohen Konzentration in der Flugasche liegt darin, dass für die Erhebung gezielt Anlagen beprobt wurden, bei denen aufgrund der eingesetzten Brennstoffe höhere PCDD/F und dl-PCB Konzentrationswerte in den Flugaschen zu erwarten waren. Alle in Deutschland gefundenen erhöhten Konzentrationswerte (478 bis 5.230 ng TEQ/kg) stehen im Zusammenhang mit der Verbrennung von Altholz der Kategorie II. Alle anderen Konzentrationswerte von Flugaschen aus den in Deutschland untersuchten Anlagen, in denen Holzhackschnitzel, Holzproduktionsreste, Rinde und Holzstaub oder Getreide verbrannt werden, liegen in ähnlichen Bereichen wie in den anderen betrachteten Ländern.

Diese Ergebnisse bezüglich der mittelgroßen Feuerungsanlagen weisen darauf hin, dass insbesondere bei der Verbrennung von Altholz Grenzwertüberschreitungen in den Flugaschen in einzelnen Fällen wahrscheinlich sind. Als Ursache kommen Verunreinigungen im Altholz in Frage, obwohl keine halogenorganischen Verbindungen enthalten sein sollten. Dennoch kann z. B. PVC häufig als typische Verunreinigung in Altholz vorkommen. Es trägt zur Gegenwart von Chlor bei der Verbrennung bei. Dadurch wird die Entstehung von PCDD/F und dl-PCB begünstigt und eine vergleichsweise hohe TEQ-Belastung der Aschen kann resultieren. Es ist daher wichtig, darauf zu achten, dass zur Verbrennung eingesetztes Altholz möglichst frei von Verunreinigungen wie z. B. PVC ist, denn dann würden die TEQ-Werte vermutlich niedriger liegen. Es wäre daher sinnvoll, wenn Betreiber und Behörden bei Anlagen die Althölzer verbrennen, sowohl die Belastung der Flugaschen kontrollieren als auch die Reinheit (im Sinne von Verunreinigungen z. B. mit PVC) der Brennstoffe besser überwachen würden.

Vergleich mit Grenzwerten und Auswirkungen geänderter Grenzwerte

Ein Vergleich der im Rahmen dieses Vorhabens gemessenen Summenkonzentrationen von PCDD/F und dl-PCB mit dem TEQ-Grenzwert von 5 µg/kg (5.000 ng/kg) zeigt, dass bei allen Anlagentypen die gemessenen gesamt-TEQ-Werte in der Regel deutlich unter dem Grenzwert von 5 µg/kg, und in den meisten Fällen auch unter einem hypothetischen Grenzwert von 1 µg/kg liegen.

In den Proben aus Einzelraumfeuerungsanlagen liegen alle Werte deutlich unter 1 µg/kg.

Bei den Festbrennstoffkesseln liegt ein gesamt-TEQ-Wert eine Flugasche mit 13.600 ng/kg TS über dem Grenzwert von 5 µg/kg. Hier wurden Reste beschichteter, lackierter oder verleimter Hölzer (Spanplatten) verbrannt. Zwei weitere gesamt-TEQ-Werte überschreiten einen Wert von 1 µg/kg, bleiben aber deutlich unter dem Grenzwert. Auch alle übrigen Ascheproben liegen deutlich darunter.

Bei den Flugaschen der mittelgroßen Feuerungsanlagen liegt ein Wert über dem Grenzwert von 5 µg/kg und ein Wert überschreitet 1 µg/kg, bleibt aber deutlich unter dem Grenzwert. Beide Werte stehen im Zusammenhang mit der Verbrennung von Altholz der Kategorie II. Die restlichen Proben liegen deutlich unter 1 µg/kg.

Auswirkungen des geänderten Grenzwertes

Die EU POP-Verordnung regelt in Artikel 7 die Bewirtschaftung von Abfällen, die POP enthalten. Abfälle, die die in Anhang IV aufgeführten POP oberhalb festgelegter Grenzwerte enthalten, werden nach Art. 7 (2) so beseitigt oder verwertet, „[...] dass die darin enthaltenen POP zerstört oder unumkehrbar umgewandelt werden, damit die verbleibenden Abfälle und Freisetzungen nicht die Eigenschaften von POP aufweisen". Die Grenzwerte des Anhang IV werden regelmäßig überprüft und an den technischen Fortschritt angepasst.

Aufgrund der recherchierten Daten und der in den beprobten Anlagen gemessenen PCDD/F und dl-PCB Gehalte lässt sich das Ausmaß der Belastung in Aschen aus Kleinfeuerungsanlagen und mittelgroßen Biomassefeuerungsanlagen in Deutschland abschätzen. Auf dieser Grundlage kann diskutiert werden, ob die Absenkung des Grenzwertes für Aschen aus Kleinfeuerungsanlagen und mittelgroßen Biomassefeuerungsanlagen sinnvoll ist.

Die Diskussion erfolgt unter Berücksichtigung einer etablierten Methode zur Ableitung von Grenzwerten nach Artikel 7(4)a der EU POP-Verordnung. Um die Bandbreite möglicher Grenzwerte einzuschränken, werden vier untere (die die Grenzwertfestsetzung nach unten begrenzen) sowie zwei obere (die die Grenzwertfestsetzung nach oben begrenzen) Begrenzungskriterien für die Grenzwertableitung herangezogen.

Die Kriterien werden im Bericht im Einzelnen diskutiert und es zeigt sich, dass alle Kriterien für beide Werte (den Grenzwert von 5 µg/kg sowie auch für einen hypothetischen Grenzwert von 1 µg/kg) erfüllt sind. Zusammenfassend lässt sich feststellen:

- Geeignete Analyseverfahren zur Kontrolle beider Werte sind wirtschaftlich verfügbar, sofern es sich um vereinzelte Stichproben handelt.
- Beide Werte liegen deutlich über der Hintergrundbelastung von Böden in Deutschland. Bodenaushub mit üblicher Hintergrundbelastung wäre nicht vom POP-Abfallregime betroffen.
- Von den Ascheproben, die im Rahmen dieser Studie untersucht wurden, überschreiten nur wenige einzelne Proben einen gesamt-TEQ (PCDD/F & dl-PCB), der über dem Grenzwert von 5 µg/kg oder einem hypothetischen Grenzwert von 1 µg/kg liegt. Die erhöhten Werte stehen im Zusammenhang mit der Verbrennung von Holz aus dem holzbe- oder verarbeitenden Gewerbe oder von Altholz der Kategorie A II. Die anfallenden Flugaschemengen und Volumina, die gegebenenfalls als POP-Abfall zu behandeln wären, sind, solange eine Vermischung von Grob- und Feinasche vermieden wird, gering. Beseitigungs- und Verwertungskapazitäten sind realistisch verfügbar. Gegebenenfalls erforderliche Entsorgungskosten sind wirtschaftlich vertretbar. Zudem hätten Betreiber bei Überschreitungen des Grenzwerts auch die Möglichkeit, durch eine verbesserte Brennstoffkontrolle den Anfall von POP-Abfällen zu vermeiden.

- Beide Werte stehen nicht im Widerspruch zu bestehenden Grenzwerten.
- Eine Absenkung des Grenzwertes trägt dazu bei, dass mögliche Auswirkungen auf Umwelt und Gesundheit vermieden werden können.

Eine weitere Absenkung des Grenzwertes (z. B. auf 1 µg/kg TEQ) wäre möglich, sofern in den betreffenden Anlagen ausschließlich unbehandeltes oder nur mechanisch behandeltes Holz verbrannt wird.

Bei Anlagen, in denen Altholz der Kategorie A II oder andere, nicht nur mechanisch be- oder verarbeitete Hölzer verbrannt werden (wie Spanplatten, beschichtete oder verleimte Hölzer, die z. B. aus Produktionsrückständen aus der Holzbe- und -verarbeitung stammen können), können erhöhte PCDD/F und dl-PCB-Gehalte auftreten. Es wäre zu prüfen, ob ein weiter gesenkter Grenzwert in solchen Fällen durch eine bessere Kontrolle des Brennstoffes einzuhalten ist. Eine Absenkung des Grenzwertes müsste dann mit entsprechenden Aufklärungsmaßnahmen einhergehen.

Zusätzlich müssten in die Prüfung auch weitere PCDD/F und dl-PCB-Quellen mit einbezogen werden.

Summary

Background and objective

This report deals comprehensively with the collection and analysis of data on the concentration of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and dioxin-like polychlorinated biphenyls (dl-PCBs) in coarse and fly ash from private wood-fired boilers (small combustion plants) and medium-sized biomass combustion plants in Germany.

PCDD/Fs and dl-PCBs are so-called ‘persistent organic pollutants’ (hereinafter referred to as ‘POPs’), which are certain substances that are toxic, remain in the environment for a long time and can be found thousands of kilometres away from their original place of manufacture or use. They pose a long-term threat to human health and ecosystems.

POPs are subject to international agreements with the overarching goal of reducing or eliminating the production, use and release of POPs as far as possible. Implementation in the European Union is governed by Regulation (EU) 2019/1021 of 20 June 2019 (EU POP Regulation). Article 7 of this Regulation governs the management of waste containing POPs. Waste containing POPs listed in Annex IV above specified limits shall be disposed of or recovered in accordance with Article 7(2) in such a way as “[...] to ensure that the POP content is destroyed or irreversibly transformed so that the remaining waste and releases do not exhibit the characteristics of POPs”.

Since dl-PCBs have toxicological properties very similar to those of PCDD/Fs, and in order to take into account the aggregate effect of all dl-PCBs, these dioxin-like compounds have been included in the existing group entry for PCDD/Fs in the EU POP Regulation. The amendment thus establishes a common threshold for PCDD/Fs and dl-PCBs, above which waste must be managed in accordance with Article 7 of the EU POP Regulation and the POP content must be destroyed (lower POP limit value of 5 µg/kg[2] , instead of the previous limit value of 15 µg/kg).

Furthermore, Member States should collect data on the content of PCDD/Fs and dl-PCBs in ash and soot from private households and fly ash from biomass plants for heat and power generation by 1 July 2026.

This report aims to contribute to this data collection from a German perspective and to provide a basis for answering the question of whether a further reduction in the limit value is feasible, taking into account scientific and technical progress. Furthermore, the levels of PCDD/F and dl-PCB determined for Germany will be discussed against the background of the reduced limit values in the EU POP Regulation for these compounds.

Initial situation

To assess the initial situation, a review of German-language literature was conducted to determine the current state of knowledge regarding the contamination of coarse and fly ash from German plants with PCDD/Fs and dl-PCBs, and the relationships between pollutant content, fuel and type of combustion.

The research focused on small combustion plants and medium-sized biomass combustion plants in Germany.

Small combustion plants are plants regulated by the 1st Federal Immission Control Ordinance (BImSchV) with a thermal output of less than 1 megawatt (MW). A distinction is made between single-room combustion systemsingle-room combustion systems

[2] 5 µg/kg = 5,000 ng/kg

("Einzelraumfeuerungsanlagen") and solid fuel boilers ("Festbrennstoffkessel"). Single-room combustion systemSingle-room combustion systems are heating devices used to heat individual rooms. These include, for example, wood-burning stoves, tiled stoves, open fireplaces and pellet stoves. In 2023, there were around 11.7 million single-room combustion systems in Germany. Solid fuel boilers are heating boilers that are also fueled by solid fuels (e.g. wood, pellets, coal) but are specifically designed to heat an entire building. In 2023, there were around 1.13 million solid fuel boilers in Germany. This research project also examined woodworking and wood processing companies that use certain fuels (specifically painted, varnished or coated wood and any resulting waste, plywood, chipboard, fibreboard or other glued wood and residues from these) where there is a suspicion that the ash may be relatively highly contaminated with PCDD/Fs and dl-PCBs.

Medium-sized biomass combustion plants within the scope of this project are those falling within the scope of the 44th BImSchV. These are plants with a rated thermal input between 1 and 50 megawatts (MW) and combustion plants requiring a permit with a rated thermal input of less than 1 MW. Plants below 1 MW that do not require a permit fall under the 1st BImSchV, whilst plants with a thermal input of 50 MW or more are generally regulated by the 13th BImSchV. There are around 40,000 medium-sized combustion plants in Germany, of which approximately 800 are solid biomass plants.

With regard to single-room combustion systems, the literature review shows that PCDD/F levels vary depending on the type of combustion plant, the fuel used and the ash fraction. In coarse ash from single-room combustion systems, PCDD/F levels are generally relatively low (<100 ng I-TEQ/kg). In fly ash, PCDD/F levels are significantly higher and can reach several thousand ng I-TEQ/kg. In some studies, high values of over 10,000 ng I-TEQ/kg have been measured.

In solid fuel boilers, the levels of PCDD/Fs in ash and soot depend on the type of fuel and the combustion technology. In coarse ash, PCDD/F levels are generally relatively low (<100 ng I-TEQ/kg), particularly when burning untreated wood. As the heating load increases, the levels of PCDD/Fs in the ash decrease. In fly ash, PCDD/F levels are usually moderate (<1,000 ng I-TEQ/kg). In some cases, levels may exceed 1,000 ng I-TEQ/kg. When burning biomass other than wood, such as straw, higher values are sometimes found, which can even reach several thousand ng I-TEQ/kg.

According to the results of the literature review, the PCDD/F levels in coarse ash obtained from the wood processing industry were very low (< 1 ng/kg TEQ BGA), whilst those in fly ash were low (< 1,000 ng/kg TEQ BGA).

According to the literature, ash from medium-sized combustion plants is generally less contaminated than ash from small combustion plants. Whilst ash from the combustion of untreated wood fuels has low toxicity values (<1 ng TEQ/kg), the combustion of treated wood results in higher values.

Selection of relevant plants, sampling and analysis

In order to collect data on PCDD/F and dl-PCB levels in ash from German small combustion plants and medium-sized biomass combustion plants, samples were taken from 20 small combustion plants and 10 medium-sized biomass combustion plants.

When selecting the 20 small combustion plants, care was taken to ensure that they represented a broad and typical cross-section of the plant stock in Germany. A total of 6 single-room combustion systems and 14 solid fuel boilers from different regions of Germany were sampled.

When selecting the medium-sized biomass combustion plants, criteria were initially established for selecting plants from the entire plant fleet in Germany. Plants where higher PCDD/F levels in the ash were to be expected were specifically included, such as those using waste wood A II, chipboard or grain as fuel. Only fly ash was sampled. The selected plants do not constitute a representative sample.

Sampling was carried out in accordance with LAGA PN 98 in the first half of 2025. The ash samples were analysed for PCDD/Fs, dl-PCBs and total chlorine. PCDD/F and dl-PCB congeners were quantified using gas chromatography coupled with a tandem mass spectrometer (GC-MS/MS). The laboratory performing the analysis is accredited for the determination of POPs such as PCDD/Fs and PCBs in accordance with DIN EN ISO/IEC 17025:2018.

Evaluation of the results

The results of the laboratory analyses are documented in the report separately for the plant categories small combustion plants (single-room combustion systems, solid fuel boilers, boilers in woodworking and wood processing plants) and medium-sized combustion plants. They are presented graphically and discussed in connection with the details of the sampled plants.

Single-room combustion systems

There is a clear trend: fly ash contains significantly higher concentrations of PCDD/Fs and dl-PCBs than coarse ash. The concentrations found vary greatly between plants and cannot be clearly attributed to individual influencing factors such as fuel type, plant age or construction method.

In coarse ash, the concentrations of PCDD/Fs and dl-PCBs were predominantly undetectable. Taking into account the limits of quantification, the calculated total TEQ value ranges between 1.05 and 1.12 ng TEQ/kg DM (WHO_{2005}). Significantly higher concentrations of PCDD/Fs and dl-PCBs were measured in the fly ash (max. 217 ng TEQ/kg DM (WHO_{2005})), which are nevertheless still below the limit value.

PCDD/Fs account for by far the largest proportion of toxicity (expressed as total TEQ). On average, PCDD/Fs in the fly ash samples contributed around 97 % to the total TEQ, whilst the proportion of dl-PCBs was around 3 %. A similar picture emerges for coarse ash. On average, PCDD/Fs in the coarse ash samples contributed around 84 % to the total TEQ, whilst the proportion of dl-PCBs was 16 %.

Solid fuel boilers

As with single-room combustion systems, the concentrations of PCDD/Fs and dl-PCBs in coarse ash are lower than in fly ash.

Most values for coarse ash are below ~2.5 ng TEQ/kg DM. Only a few samples contain slightly elevated concentrations of PCDD/Fs and dl-PCBs (max. 100 ng TEQ/kg DM).

Significantly higher total TEQ concentrations were found in the fly ash; in the smaller boilers up to 38 kW, up to 372 ng TEQ/kg DM (PCDD/Fs & dl-PCBs). In the larger boilers from 38 kW, particularly those used in the wood processing industry, the TEQ values were conspicuously high. The highest total TEQ concentrations (maximum 13,643 ng/kg DM (PCDD/Fs & dl-PCBs)) were found in the fly ash from plants in which fuels such as chipboard residues or wood from the wood processing industry were burned. In contrast, natural wood used as fuel resulted in significantly lower TEQ values in the range of 1.75 to 2.47 ng/kg DM.

PCDD/Fs account for by far the largest proportion of toxicity. On average, PCDD/Fs in the fly ash samples contributed around 99 % to the total TEQ, whilst the proportion of dl-PCBs was around 1 %. In the coarse ash, PCDD/Fs in the coarse ash samples contributed around 97 % to the total TEQ, whilst the proportion of dl-PCBs was 3 %.

Medium-sized combustion plants

When selecting the plants, those where higher PCDD/F and dl-PCB contents in the ash were expected were specifically included. As expected, the concentration values determined for fly ash from medium-sized biomass combustion plants therefore show significantly higher median and mean values overall (119 and 846 ng TEQ/kg DM; maximum value 5,230 ng TEQ/kg DM) than those from small combustion plants, except for fly ash from boilers in the woodworking and processing industry.

Conclusion

In principle, the results indicate that coarse ash is generally very low in contamination (max. 100 ng TEQ/kg DM) and fly ash generally has higher concentrations, which are usually well below existing regulatory limits. High concentrations, in the range of several thousand ng TEQ/kg DM, occur at the sampled plants exclusively in connection with the incineration of waste wood or other processed wood. In individual cases, PCDD/F and dl-PCB TEQ values above the existing limit of 5,000 ng/kg TEQ may also occur.

The largest proportion of toxicity in both coarse and fly ash is caused by PCDD/Fs. The proportion of dl-PCBs is usually a few percentage points.

Pollutant loads

For the purpose of evaluating and discussing the impact of a possible change to the Annex IV limit value for PCDD/Fs and dl-PCBs in the EU POP Regulation, the pollutant loads contained in the ash from small combustion plants were determined. These can be calculated by multiplying the average or mean concentration present in the ash by the ash quantities.

The calculations were carried out for small combustion plants, broken down by plant type, for single-chamber combustion plants, solid fuel boilers and boilers in wood processing and manufacturing plants, and separately for coarse ash and fly ash.

With regard to medium-sized combustion plants, it is not possible to estimate the loads of PCDD/Fs and dl-PCBs on the basis of the available data for various reasons.

In total, the annual TEQ loads for PCDD/Fs and dl-PCBs in ash from the small combustion plants considered are in the low single-digit gram range. The vast majority of the TEQ load in both coarse ash and fly ash stems from PCDD/F contamination. According to the estimates made in the report, the loads in coarse ash (ash quantity ~129 kt) total approx. 0.6 g and in fine ash (ash quantity ~8.7 kt) approx. 1.8 g (based on mean values). This also suggests that about ¼ of the total TEQ load is contained in the coarse ash and ¾ in the fly ash.

Comparison of the results with literature references

A comparison of the PCDD/F and dl-PCB concentrations in coarse and fly ash measured in this project with values from the specialist literature for Germany shows that the results of the investigations carried out as part of this project are generally consistent with the information from the literature studies, even if they may differ in detail.

In a further comparison, the measured values were compared with corresponding values from other European countries. Overall, the results show that the levels in Germany are within the range of values reported from other countries. Soot samples from the chimneys of small wood-burning plants clearly show that PCDD/F pollution depends heavily on the fuel used. When burning natural wood and paper for kindling, the PCDD/F concentrations are relatively low. However, as soon as treated or contaminated wood, plastics, aluminium foil, cardboard or household waste are co-incinerated, the measured values rise sharply. This partly explains the high PCDD/F values reported in the literature from other countries.

In this project, values were measured in medium-sized combustion plants that were in some cases several orders of magnitude higher than those reported for wood combustion in the literature examined. However, this does not mean that the contamination of these fly ashes in Germany is higher than in the other countries considered. The reason for the comparatively high concentrations in fly ash in Germany is that the survey specifically sampled plants where higher PCDD/F and dl-PCB concentrations in fly ash were to be expected due to the fuels used. All elevated concentrations found in Germany (478 to 5,230 ng TEQ/kg) are related to the incineration of category II waste wood. All other concentrations of fly ash from the plants investigated in Germany, where wood chips, wood production residues, bark and wood dust or grain are incinerated, are in a similar range to those in the other countries considered.

These results for medium-sized combustion plants indicate that, particularly in the case of waste wood combustion, limit values are likely to be exceeded in fly ash in individual cases. Contamination in waste wood may be the cause, although no halogenated organic compounds should be present. Nevertheless, PVC, for example, is often found as a typical contaminant in waste wood. It contributes to the presence of chlorine during combustion. This promotes the formation of PCDD/Fs and dl-PCBs and can result in a comparatively high TEQ contamination of the ash. It is therefore important to ensure that waste wood used for combustion is as free as possible from contaminants such as PVC, as this would probably result in lower TEQ values. It would therefore be advisable for operators and authorities at plants that incinerate waste wood to monitor more closely both the contamination of fly ash and the purity (in terms of contaminants such as PVC) of the fuels.

Comparison with limit values and effects of changed limit values

A comparison of the total concentrations of PCDD/Fs and dl-PCBs measured in this project with the TEQ limit value of 5 µg/kg (5,000 ng/kg) shows that for all types of plants, the measured total TEQ values are generally well below the limit value of 5 µg/kg and in most cases also below a hypothetical limit value of 1 µg/kg.

In the samples from single-room combustion systems, all values are well below 1 µg/kg.

In the case of solid fuel boilers, one total TEQ value for fly ash at 13,600 ng/kg TS exceeds the limit value of 5 µg/kg. In this instance, residues of coated, painted or glued wood (chipboard) were burned. Two other total TEQ values exceed 1 µg/kg, but remain well below the limit value. All other ash samples are also well below this value.

In the fly ash from medium-sized combustion plants, one value exceeds the limit value of 5 µg/kg and one value exceeds 1 µg/kg, but remains well below the limit value. Both values are related to the incineration of category II waste wood. The remaining samples are well below 1 µg/kg.

Effects of the amended limit value

Article 7 of the EU POP Regulation governs the management of waste containing POPs. Waste containing POPs listed in Annex IV above specified limit values shall be disposed of or recovered in accordance with Article 7(2) in such a way as “[...] to ensure that the POPs contained therein are destroyed or irreversibly transformed so that the remaining waste and releases do not exhibit the characteristics of POPs”. The limit values in Annex IV are regularly reviewed and adapted to technical progress.

Based on the data researched and the PCDD/F and dl-PCB levels measured in the sampled plants, it is possible to estimate the extent of contamination in ash from small combustion plants and medium-sized biomass combustion plants in Germany. On this basis, it can be discussed whether it makes sense to lower the limit value for ash from small combustion plants and medium-sized biomass combustion plants.

The discussion takes into account an established method for deriving limit values in accordance with Article 7(4)(a) of the EU POP Regulation. In order to narrow down the range of possible limit values, four lower (which limit the limit value setting downwards) and two upper (which limit the limit value setting upwards) limiting criteria are used for the limit value derivation.

The criteria are discussed in detail in the report, and it is shown that all criteria are met for both values (the limit value of 5 µg/kg and a hypothetical limit value of 1 µg/kg). In summary, it can be stated that:

- Suitable analytical methods for monitoring both values are economically viable, provided that only isolated samples are taken.
- Both values are significantly above the background contamination levels of soils in Germany. Excavated soil with normal background contamination would not be affected by the POP waste regulations.
- Of the ash samples examined in this study, only a few individual samples exceed a total TEQ (PCDD/Fs & dl-PCBs) that is above the limit value of 5 µg/kg or a hypothetical limit value of 1 µg/kg. The elevated values are related to the incineration of wood from the woodworking or wood processing industry or from category A II waste wood. The quantities of fly ash produced, which may need to be treated as POP waste, are low provided that mixing of coarse and fine ash is avoided. Disposal and recovery capacities are realistically available. Any disposal costs that may be necessary are economically reasonable. Furthermore, if the limit value is exceeded, operators would also have the option of avoiding the accumulation of POP waste through improved fuel control.
- Neither value conflicts with existing limit values.
- Lowering the limit value helps to avoid potential impacts on the environment and health.

A further reduction in the limit value (e.g. to 1 µg/kg TEQ) would be possible if only untreated or mechanically treated wood were incinerated in the plants concerned.

Plants that burn waste wood of category A II or other wood that has not been treated or processed exclusively by mechanical means (such as chipboard, coated or glued wood, which may originate from production residues from wood processing) may have elevated PCDD/F and dl-PCB levels. It would need to be examined whether a further reduction in the limit value can be achieved in such cases through better control of the fuel. A reduction in the limit value would then have to be accompanied by appropriate awareness-raising measures.

In addition, other sources of PCDD/Fs and dl-PCBs would also have to be included in the assessment.

1 Background and objectives

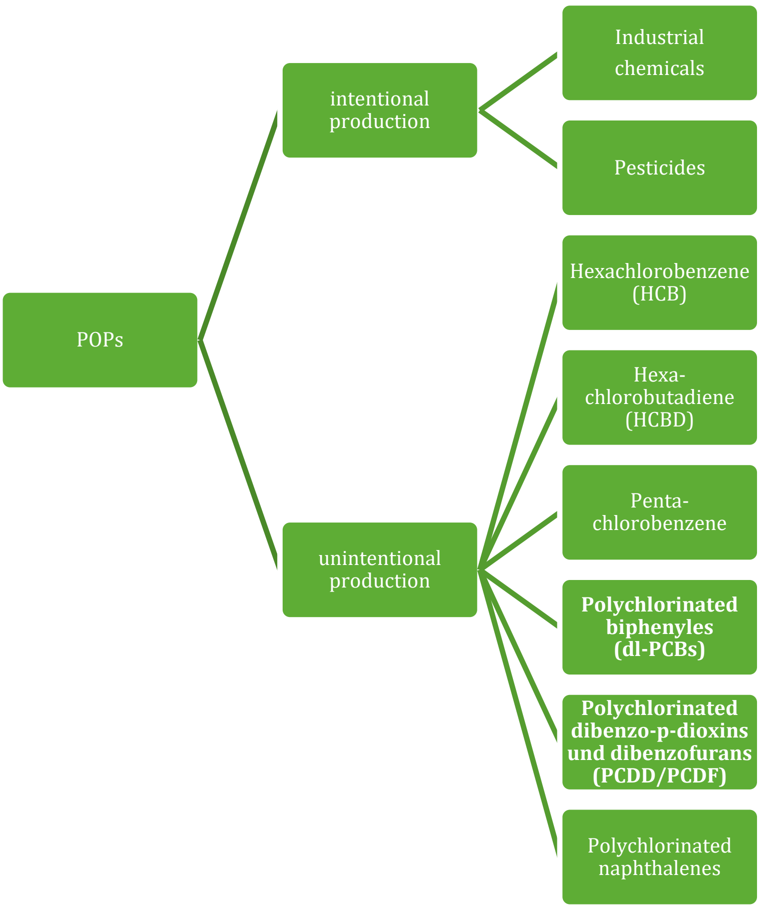
1.1 Background

Persistent organic pollutants (hereinafter 'POPs') is the collective term for certain substances that are toxic, persist in the environment over the long term and can be found thousands of kilometres away from their original place of manufacture or use. POPs therefore pose a long-term threat to human health and ecosystems.

POPs are predominantly intentionally manufactured substances with a wide range of applications. Some POPs, including polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF) as well as dioxin-like polychlorinated biphenyls (dl-PCBs), can be unintentionally produced during combustion or industrial manufacturing processes.

POPs can be divided into unintentionally and intentionally produced POPs. The former are or were produced industrially and include various industrial chemicals and pesticides (currently a total of 33 substances or groups of substances; as of November 2025). The latter are produced unintentionally. Currently, six unintentionally produced POPs are listed under the Stockholm Convention. Parties to the Stockholm Convention are required to take specific measures to reduce their release from anthropogenic sources. Unintentionally produced POPs include, among others, PCDD/Fs and dl-PCBs (see Figure 1).

Figure 1: Categories of POPs



Source: Own illustration, Ramboll. Based on the Stockholm Convention[3]

[3] List of POPs in the Stockholm Convention (accessed on 18 November 2025).

POPs are covered by the Stockholm Convention on POPs and the POPs Protocol under the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP). Both international agreements have the overarching aim of reducing or eliminating production, use and release of these substances as far as possible. The Stockholm Convention is implemented in Europe by Regulation (EU) 2019/1021 of 20 June 2019 (EU POPs Regulation).

Article 7 of the EU POP Regulation governs the management of waste containing POPs. Waste containing or contaminated by the POPs listed in Annex IV in concentrations exceeding the specified limit values shall, pursuant to Article 7(2), be disposed of or recovered '[...] *in such a way as to ensure that the POP content is destroyed or irreversibly transformed, so that the remaining waste and releases do not exhibit the characteristics of POPs*'.

The limit values in Annex IV are reviewed regularly and adapted to technical progress. As part of this review, the European Parliament and the Council of the European Union adopted Regulation (EU) 2022/2400 on 23 November 2022 amending Regulation (EU) No 2019/1021 on POPs.

The limit values set out in Annex IV apply, amongst other things, to waste relevant to the project, namely ash and soot from private households, as well as fly ash from biomass plants used for heat and electricity generation. An overview of the previous, current and hypothetical limit values is provided at Table 1) and Table 2). A hypothetical limit value is given here because the Commission is to review the concentration limit of 5 µg TEQ/kg with a view to lowering the value, provided this is feasible in the light of scientific and technical progress. Any value below 5 µg TEQ/kg would be possible. The hypothetical value of 1 has been chosen here solely to provide a specific value for assessing a possible reduction. An assessment could also be carried out for other values below 5.

Table 1: Limit values for PCDD/Fs and dl-PCBs in ash and soot from private households

Limit value	Validity	Value	POP	Source
Previous limit value	Until 31 December 2024	15 µg TEQ/kg	PCDD/Fs	Annex IV of the EU POP Regulation
Current limit value	Since 1 January 2025	5 µg TEQ/kg	PCDD/Fs and dl-PCBs	Regulation (EU) 2022/2400 amending Annexes IV and V to the EU POP Regulation
Hypothetical limit value	Review of the limit value by 2027	1 µg TEQ/kg	PCDD/Fs and dl-PCBs	Regulation (EU) 2022/2400 amending Annexes IV and V to the EU POPs Regulation (review pursuant to Article 2 by 30 December 2027)

Table 2: Limit values for PCDD/Fs and dl-PCBs in fly ash from biomass plants for heat and power generation

Limit value	Validity	Value	Pollutant	Source
Previous limit value	Until 30 December 2023	10 µg TEQ/kg	PCDD/Fs	Annex IV of the EU POP Regulation

Limit value	Validity	Value	Pollutant	Source
Current limit value	Since 31 December 2023	5 µg TEQ/kg	PCDD/Fs and dl-PCBs	Regulation (EU) 2022/2400 amending Annexes IV and V to the EU POP Regulation
Hypothetical limit value	Review of the limit value by 2027	1 µg TEQ/kg	PCDD/Fs and dl-PCBs	Regulation (EU) 2022/2400 amending Annexes IV and V to the EU POPs Regulation (review pursuant to Article 2 by 30 December 2027)

PCDD/PCDF and dl-PCBs in ash and soot from German small combustion plants and medium-sized biomass combustion plants

As the substances in a subgroup of 12 PCB congeners, known as dl-PCBs, have toxicological properties very similar to those of PCDD/PCDF, and in order to take account of the aggregate effect of all dl-PCBs, these dioxin-like compounds have been included in the existing group entry for PCDD/PCDF in Annexes IV and V of Regulation (EU) 2019/1021. The amendment thus establishes a common threshold for PCDD, PCDF and dl-PCBs, above which waste must be managed in accordance with Article 7 of the EU POPs Regulation and the POP content must be destroyed (lower POP limit of 5 µg/kg instead of the previous 15 µg/kg). The text of the Regulation states: “The Commission shall review this concentration limit and, if necessary, submit a legislative proposal by 30 December 2027 at the latest to lower this limit, provided that such a reduction is feasible in the light of scientific and technical progress.”

The concentration values are calculated as the sum of the PCDD, PCDF and dl-PCB concentrations and are based on the toxicity equivalence factors (TEFs) for PCDDs, PCDFs and dl-PCBs set out in the table in Annex V, Part 2, paragraph 3 of Regulation (EU) 2022/2400. These TEFs correspond to those of the WHO’s 2005 TEF concept (see chapter 2.3)

Furthermore, Member States are required to collect data on the levels of PCDD/PCDF and dl-PCBs in ash and soot from private households, as well as fly ash from biomass plants used for heat and electricity generation, by 1 July 2026[4].

New POPs and candidate POPs

The list of POPs under the Stockholm Convention is constantly being expanded, as new chemicals with POP properties continue to be identified by Parties and proposed for inclusion. The assessment of these so-called POP candidates against established criteria is carried out by a scientific advisory body, the POP Review Committee (POP RC), which submits a proposal to the Conference of the Parties for inclusion in Annexes A (elimination), B (restriction) or C (undesirable by-products). The Conference of the Parties, which takes place every two years, decides on the inclusion of further substances.

[4] Regulation (EU) 2022/2400 amending Annexes IV and V to the EU POPs Regulation (Recital 5 of the Regulation)

At the 11th Conference of the Parties (COP 11) in May 2023, three new POPs were added to the Stockholm Convention (SC). These include the following compounds:

- UV 328
- Dechloran Plus
- Methoxychlor (possibly no longer relevant in Germany, as it has not been authorised as a pesticide since 2002)

In May 2025, at the 12th Conference of the Parties (COP 12), it was decided to include three further new POPs in the SC. These are the following compounds:

- Medium-chain chlorinated paraffins (MCCP)
- Long-chain perfluorocarboxylic acids (Long-chained PFCA)
- Chlorpyrifos

Extensive scientific data on these substances has already been compiled within the POP RC and at European level (particularly in the context of preparing restriction dossiers under the REACH Regulation). Furthermore, these substances are being investigated in numerous scientific articles. The data available on the occurrence of these compounds in waste and recyclates in Germany is currently still insufficient. There is also a lack of recommendations for the environmentally sound treatment of affected waste streams, as well as an assessment of potential risks associated with waste treatment. This is where the project aims to step in and provide an initial data foundation for Germany.

1.2 Objectives

The research project is intended to achieve the following objectives in accordance with the terms of reference:

1. Collection of data on PCDD/PCDF and dl-PCB concentrations in ash from small and medium-sized biomass combustion plants in Germany by 1 July 2026

   With this objective, the project aims to contribute to fulfilling the obligations set out in Recital 5 of Regulation (EU) 2022/2400 amending Annexes IV and V of the EU POP Regulation. Furthermore, the PCDD/PCDF and dl-PCB levels to be determined are to be discussed in the context of the lowered limit values for these compounds in the EU POP Regulation.

2. Provision of a robust data basis on the occurrence and concentrations of new POPs and POP candidates in waste and recyclates in Germany

   A further objective is to provide information on affected waste streams and the concentrations of new POPs and POP candidates in the identified waste and recyclates. The risks to humans and the environment associated with the management of affected waste streams and recyclates are to be assessed, and corresponding proposals for environmentally sound treatment options derived. Furthermore, against the backdrop of the regular evaluation of the EU POPs Regulation, both existing limit values in Annex IV of the EU POPs Regulation are to be discussed and new limit value ranges proposed.

This report is devoted exclusively to presenting the results of the first part of the project, namely the collection of data on the levels of PCDD/PCDF and dl-PCBs in ash from small and medium-sized biomass combustion plants in Germany. The results of the second part of the project will be presented in a separate report.

2 Review of the initial situation (literature review)

The research focused mainly on German literature sources in order to gain an overview of German combustion plants. However, literature sources from other countries were also considered where they contained relevant information on PCDD/F and dl-PCB concentrations in bottom and fly ash from those countries. All identified literature sources will be reviewed for relevance in the course of the study.

The research utilised the internet in general, Google Scholar, Europe PMC, and PubMed to identify additional publications documenting the concentrations of chlorine, PCDD/Fs and dl-PCBs in ash from small-sized and medium-sized combustion plants. The search terms used in specific combinations were 'PCDD/F*', 'dl-PCB*', 'dioxins*', 'Cl', 'chlorine*', 'small-sized combustion plant*', 'medium-sized combustion plant*', "ash", "soot", "combustion plant*", "Germany", "wood", "wood ash", "soot ash", "biomass ash", "straw", "cereals", "chipboard", "wood-processing industry".

The compiled data is summarised in an Excel file for the literature review on Work Package 1 (hereinafter referred to as the 'Excel file')[5]. In addition to the PCDD/F and dl-PCB content in bottom ash and fly ash, all extracted information is listed there, including the literature source, author, link and year. Additionally, the project team asked relevant associations, such as the German Wood Energy Association, about studies relevant to the project; however, no additional data could be obtained in this way.

A total of eight literature sources containing relevant information on the concentrations of PCDD/Fs and dl-PCBs in bottom ash and fly ash were identified. In the case of review studies, the original literature sources were examined and the information extracted from them. If the original study was not publicly accessible, the information was taken from the review article. Where necessary, the extracted concentrations of chlorine, PCDD/Fs and dl-PCBs were converted into the appropriate units to facilitate comparison of the results.

The literature review focused, among other things, on sources containing information on PCDD/Fs and dl-PCBs in bottom and fly ash from medium-sized biomass combustion plants equipped with electrostatic precipitators or fabric filters. The 44th BImSchV has been in force in Germany since 2019; its emission limit values for dust from medium-sized biomass combustion plants can only be met with electrostatic precipitators or fabric filters. The transition period for existing plants with a rated thermal input of 5 MW or more ended on 31 December 2024. From 2025, a cyclone separator alone will no longer be sufficient. Information from studies on older plants no longer reflects the current state of the art.

Relevant information is presented and discussed in the following chapters.

2.1 Substances under consideration

Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs)

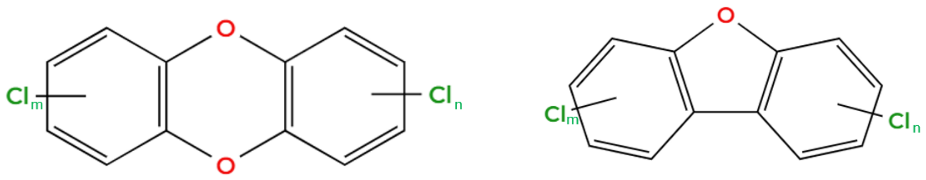
Polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are closely related groups of persistent organic pollutants known for their high toxicity and environmental persistence. Often referred to as 'dioxins and furans', PCDD/Fs consist of chlorinated compounds that share similar chemical structures and toxicological properties.

PCDDs and PCDFs consist of two benzene rings linked either by two oxygen atoms (in PCDDs) or an oxygen bridge (in PCDFs). Chlorine atoms can bind to the carbon atoms of these rings at various positions, resulting in the formation of 210 different congeners (variants), 17 of which

[5] The Excel file is provided separately with the interim report.

are particularly toxic. Among these, 2,3,7,8-tetrachlorodibenzodioxin (TCDD) is considered the most toxic and serves as a reference compound for assessing the toxicity of other dioxins and furans. The structural formula of this group of substances is shown in Figure 2.

Figure 2: General structural formula of dibenzodioxins (left) and dibenzofurans (right)



Source: Own illustration, Ramboll. Using MolView (2025).

Neither PCDDs nor PCDFs have been intentionally produced, except in very small quantities for analytical and research purposes. They are formed unintentionally as by-products of various industrial processes, particularly thermal and combustion processes (e.g. waste incineration, combustion of solid and liquid fuels, or metal production using thermal processes) as well as chemical production processes (UNEP, 2013; UNEP, 2019).

As described above, PCDD/Fs are formed unintentionally during combustion processes, among other things, particularly when organic material is burned in the presence of chlorine (UNEP, 2019). The properties of the fuel also play a significant role in the formation of PCDD/Fs during biomass combustion. During wood combustion, PCDD/Fs are typically formed from precursors such as phenols and lignin, or through *de novo* reactions in the presence of particulate carbon and chlorine (UNEP, 2013). High emissions are to be expected particularly during the combustion of treated wood (Pieper, 2001) and treated wood waste (Ministry of the Environment and Transport, BW, 2003), but also during the combustion of straw and grain (TLLR, 2020; Launhardt et al., 2000). Dioxin emissions from wood-burning plants are a particular concern, especially when treated, varnished or PVC-coated wood is burned, as this can result in high PCDD/F emissions (Lavric et al., 2004).

Certain factors promote the formation of PCDD/Fs during combustion (UNEP, 2013):

- Technology: incomplete combustion, poor mixing and inadequate flue gas treatment promote the formation of PCDD/Fs
- Temperature: PCDD/Fs form at 200–650°C, most intensively between 200–450 °C with a maximum at 300 °C
- Chlorine: Chlorine is essential for formation, regardless of its form. Chlorine in fly ash or in its elemental form in the gas can particularly influence formation
- Metals: Metals such as copper, iron, zinc, aluminium, chromium and manganese act as catalysts for the formation of PCDD/Fs
- Sulphur and nitrogen: Sulphur and nitrogen compounds can inhibit formation, but may also cause other by-products.

Operators' practices have a significant influence on the factors mentioned and therefore on the formation of PCDD/Fs (as well as dl-PCBs). For this reason, the 1st BImSchV contains requirements for operators of manually fed combustion plants for solid fuels. Operators are obliged to seek advice from a chimney sweep regarding the proper operation of the combustion plant, the correct storage of fuel and the specific requirements for handling solid fuels.

Furthermore, the combustion plant must be in good working order and must be operated in accordance with the manufacturer's instructions.

PCDD/Fs can be destroyed during incineration under suitable conditions. Temperatures in the range of 1,100 to 1,200 °C are considered suitable for the destruction of halogenated pollutants, including PCDD/Fs (Huygens et al., 2019).

According to Vehlow et al., there is a close correlation between the PCDD/F content in the ash and the organic carbon content. If the carbon content in the ash is below 1 %, the PCDD/F levels are generally less than 20 ng WHO toxicity equivalents per kilogram (Vehlow et al., 2006 cited in Huygens et al., 2019). However, the adsorption of PCDD/Fs in fly ash can be comparatively high, depending on the amount of elemental carbon or soot particles, as inorganic surfaces have a low adsorption potential for PCDD/Fs (Vehlow et al., 2006 cited in Huygens et al., 2019).

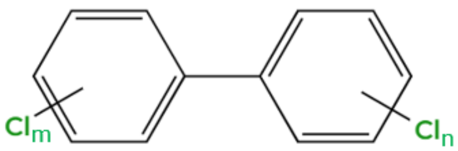
Ash from small combustion plants in which waste wood or other waste, e.g. plastics such as PVC, has been incinerated, can contain high levels of dioxins. According to a study, even small quantities of treated wood or admixtures of packaging materials such as plastics can significantly increase pollutant levels in the air (Gras et al., 2009). Ash from the combustion of untreated wood generally contains low levels of dioxins (Behnke et al., 2018).

Dioxin-like polychlorinated biphenyls (dl-PCBs)

Dioxin-like polychlorinated biphenyls (dl-PCBs) are a subgroup of PCBs that exhibit toxic effects similar to those of dioxins and furans, including disruption of the endocrine and immune systems. Like dioxins and furans, dl-PCBs are classified as persistent organic pollutants, known for their environmental persistence, bioaccumulation and long-term health risks to humans and animals (Behnke et al., 2018).

PCBs are chlorinated aromatic compounds consisting of two benzene rings to which chlorine atoms can be attached at various positions (see Figure 3). Of the total of 209 possible PCB congeners, 12 exhibit dioxin-like toxicity (Behnke et al., 2018).

Figure 3: General structural formula of polychlorinated biphenyls



Source: Own illustration, Ramboll. Using MolView (2025).

According to Lemieux et al., dl-PCBs are formed via a similar mechanistic pathway to PCDD/Fs (Lemieux et al., 2001). Maximum PCB formation occurs at temperatures of around 350 °C (Lemieux et al., 2001). At higher combustion temperatures (e.g. above 1,200 °C), dl-PCBs are effectively destroyed. However, dl-PCBs are also effectively destroyed at lower temperatures (e.g. 950 °C) and under suitable combustion conditions such as sufficient turbulence and residence time (Lemieux et al., 2001).

2.2 Focus on plants and fuels

2.2.1 Small combustion plants

Small combustion plants considered within the scope of this project are those regulated by the 1. BImSchV and which use wood as fuel.

The 1. BImSchV regulates the installation, maintenance and operation of small combustion plants in Germany and aims to reduce air pollution from smaller heating and combustion systems. This regulation primarily concerns heating systems and boilers in residential and commercial buildings with a **thermal output of less than 1 megawatt** (MW), including single-room combustion systems such as woodburning, tiled and pellet stoves.

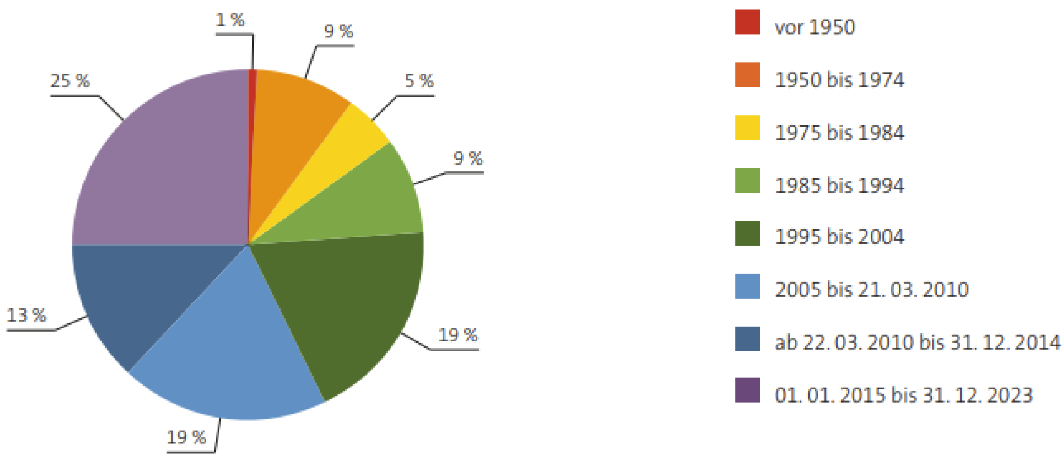
The 1. BImSchV distinguishes between **single-room combustion systems and solid fuel boilers**.

Single-room combustion systems are heating appliances designed to heat individual rooms. These include, for example, wood-burning stoves, tiled stoves, open fireplaces and pellet stoves. They usually serve as supplementary or secondary heating and not as the main heating source for a building. They release heat directly into the room in which they are installed. They are generally fueled by solid fuels such as logs, pellets or briquettes. The heat generated is released directly into the room in which the appliance is located. They rarely have a mechanism for channeling the heat into other rooms or into the central heating system (1. BImSchV, UBA, 2023).

Single-room heating systems, such as wood-burning stoves and tiled stoves, come in many different designs. They are often used as supplementary heating to improve comfort in a single room. Their heat output is usually less than 15 kW (Launhardt et al., 1998).

According to the Federal Association of Chimney Sweeps, there were around 11.7 million single-room combustion systems in Germany in 2023 (ZIV, 2023). An overview of single-room combustion systems for solid fuels by year of manufacture or date on the system’s type plate (in per cent) is shown in Figure 4. Around a quarter of the systems were installed or type-approved from 2015 onwards. Around a further quarter were installed before 1995. Around half of the systems date from the period between 1995 and 2014.

Figure 4: Overview of single-room combustion systems for solid fuels by year of construction or date on the plant’s type plate (in %).



Source: ZIV (2023)

Solid fuel boilers are heating boilers that are also fueled by solid fuels (e.g. wood, pellets, coal) but are specifically designed to heat an entire building. According to the Federal Association of Chimney Sweeps, there were around 1.13 million solid fuel combustion systems (so-called solid fuel boilers) in 2023 (excluding single-room combustion systems) (ZIV, 2023). According to

Regulation (EU) 2015/1189[6] , the term 'solid fuel boiler' is *"a device with one or more solid fuel-based heat generators that supplies heat to a water-based central heating system in order to bring the internal temperature of one or more enclosed spaces to the desired temperature and maintain it there (and which loses no more than 6 % of its rated heat output to its surroundings)"*[7].

Although the regulation permits fuels such as wood, pellets and certain types of coal, this project considers only wood fuels such as wood chips, pellets and logs. According to the regulation (1st Federal Immission Control Ordinance, Section 3(1)), these include:

"3. natural, lumpy wood including adhering bark, in particular in the form of logs and wood chips, as well as brushwood and cones,

4. natural, non-chunky wood, in particular in the form of sawdust, shavings and sanding dust, as well as bark,

5a. compressed products made from natural wood in the form of wood briquettes in accordance with DIN 51731, October 1996 edition, or in the form of wood pellets in accordance with the fuel-related requirements of the DINplus certification programme 'Wood pellets for use in small-scale fireplaces in accordance with DIN 51731-HP 5', August 2007 edition, as well as other wood briquettes or wood pellets made from untreated wood of equivalent quality,

6. painted, varnished or coated wood, as well as any resulting waste, provided that no wood preservatives have been applied or are present as a result of treatment, and that coatings do not contain any organohalogen compounds or heavy metals,

7. Plywood, chipboard, fibreboard or other glued wood, as well as any resulting residues, provided that no wood preservatives have been applied or are present as a result of treatment and that coatings do not contain any halogenated organic compounds or heavy metals, …"[8]

It is important to note that the fuels referred to in Section 3(1)(6) or (7) may only be used in combustion plants with a rated thermal input of 30 kilowatts or more and only in woodworking or wood-processing establishments.

The new EU POPs Regulation sets limit values for PCDD/F and dl-PCB concentrations in ash from private households, above which the ash must be treated in such a way that the PCDD/Fs and dl-PCBs it contains are destroyed or irreversibly transformed. Nevertheless, this research project will also examine woodworking or wood processing facilities that use fuel types 6 or 7 and have a rated thermal input of more than 30 kW. By analysing the ash from these plants, it is possible to investigate whether commercial wood material used as fuel contributes to elevated concentrations of PCDD/Fs.

If elevated levels are detected, this could indicate a need for further measures and, where necessary, additional monitoring of such facilities.

2.2.2 Medium-sized biomass combustion plants

Medium-sized combustion plants within the scope of this project are those falling within the scope of the 44th BImSchV. This regulation has been in force since 13 June 2019.

[6] COMMISSION REGULATION (EU) 2015/1189 – of 28 April 2015 – implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to the setting of ecodesign requirements for solid fuel boilers

[7] English translation is provided for the purpose of this study. For legal interpretation and application, the German law (1. BImSchV) shall prevail.

[8] English translation is provided for the purpose of this study. For legal interpretation and application, the German law (1. BImSchV) shall prevail.

Medium-sized combustion plants within the meaning of this regulation are plants with a thermal input of between 1 and 50 megawatts (MW) as well as combustion plants requiring a permit with a thermal input of less than 1 MW. Installations below 1 MW that do not require a permit fall under the 1st BImSchV (see chapter 2.2.1), whilst installations with a thermal input of 50 MW or more are generally regulated by the 13th BImSchV.

In Germany, there are around 40,000 medium-sized combustion plants (TÜV SUD, 2020), of which approximately 800 are combustion plants for solid biomass[9].

On 25 November 2015, the European Parliament and the Council adopted Directive (EU) 2015/2193 on the limitation of emissions of certain pollutants into the air from medium combustion plants. This Directive forms part of the EU's Clean Air Package. Until now, the requirements for plants falling within the scope of Directive (EU) 2015/2193 have been regulated both in the Technical Instructions on Air Quality Control (TA-Luft) and in the Ordinance on Small and Medium-Sized Combustion Plants (1st BImSchV). They are now being consolidated in the 44th BImSchV and adapted to the state of the art.

Within the scope of this project, the focus is on biomass fuels, which are defined in the 44th BImSchV as follows:

'Biofuels within the meaning of this Ordinance are:

1. products of agricultural or forestry origin derived from plant material or parts thereof, provided they are used to utilise their energy content, and

2. the following wastes, provided that the heat generated is utilised:

a) plant waste from agriculture and forestry;

b) plant waste from the food industry;

c) natural, non-hazardous wood from landscape management, provided that, due to its physical properties, it is comparable to wood from forestry;

d) fibrous plant waste and liquor from the production of natural pulp and from the production of paper from pulp, provided that they are co-incinerated at the place of production;

e) cork waste;

f) wood waste, with the exception of wood waste which, as a result of treatment with wood preservatives or coating, may contain halogenated organic compounds or heavy metals; this includes, in particular, wood waste from construction and demolition waste."[10]

As many medium-sized combustion plants use waste wood of categories I and II as fuel, plants in which waste wood of these categories is incinerated will be sampled as part of this project. Higher PCDD/F and PCB levels are to be expected during the combustion of Category II waste wood and during the combustion of roadside vegetation, which is also covered as a fuel by the 44th BImSchV. For example, a 2003 study by the Ministry of the Environment and Transport, Baden-Württemberg, identified comparatively high PCDD/F levels in bottom ash and fly ash from solid fuel boilers used for the combustion of roadside vegetation (54–1,114 ng I-TEQ/kg) (Ministry of the Environment and Transport, BW, 2003).

[9] Information from the Federal Environment Agency in December 2024

[10] English translation is provided for the purpose of this study. For legal interpretation and application, the German law (44. BImSchV) shall prevail.

2.3 Results

Background on TEF concepts

When comparing the TEQ concentrations of PCDD/Fs and dl-PCBs in bottom ash and fly ash from small and medium-sized biomass combustion plants, it should be noted that various TEF concepts have been developed over the years. These concepts serve to assess the toxicity of dioxins and similar compounds on the basis of toxicity equivalent factors (TEF) and to express this in terms of toxicity equivalents (TEQ). These concepts have evolved over time, leading to differences in the calculation methods and the resulting TEQ levels.

The development of TEQs began in the 1980s with the introduction of the I-TEQ system for PCDD/Fs, which was formalised by NATO (*Committee on the Challenges of Modern Society;* NATO-CCMS) (Kutz et al., 1990). TEQs had already been developed previously by the Federal Health Office (BGA), which provided a basis for the assessment of PCDD/Fs (Pieper, 2001). In the 1990s, the system was expanded to include dl-PCBs, and in 1998 the WHO-TEQs were developed (Van der Berg, 1998). In 2005, the WHO-TEFs were further refined and updated based on new toxicological data (Van der Berg, 2006). In 2022, the TEFs were revised again by the WHO (DeVito et al., 2024) to incorporate the latest scientific findings into the assessment of dioxin-like compounds. Although this update reflects advances in toxicology, it has not yet been widely adopted in regulatory requirements.

For example, the EU POPs Regulation continues to be based on the 2005 TEF values. These TEFs, as well as those from other TEF frameworks, are summarised in Table 3. The TEF is a factor that describes the toxicity of a single substance in comparison to the most toxic dioxin, whilst the TEQ is the overall result that expresses the toxicity of a mixture of substances using these factors.

Table 3: TEFs for PCDDs, PCDFs and dl-PCBs according to various TEF concepts.

PCDD/F and dl-PCB	CAS Number	TEF (BGA)	NATO (I-TEF) 1988	WHO 1998 TEF	WHO 2005 TEF	WHO 2022 TEF*
PCDD						
2,3,7,8-TeCDD	1746-01-6	1	1	1	1	1
1,2,3,7,8-PeCDD	40321-76-4	0.1	0.5	1	1	0.4
1,2,3,4,7,8-HxCDD	39227-28-6	0.1	0.1	0.1	0.1	0.09
1,2,3,6,7,8-HxCDD	57653-85-7	0.1	0.1	0.1	0.1	0.07
1,2,3,7,8,9-HxCDD	19408-74-3	0.1	0.1	0.1	0.1	0.05
1,2,3,4,6,7,8-HpCDD	35822-46-9	0.01	0.01	0.01	0.01	0.05
OCDD	3268-87-9	0.001	0.001	0.0001	0.0003	0.001
PCDF						
2,3,7,8-TeCDF	51207-31-9	0.1	0.1	0.1	0.1	0.07

PCDD/F and dl-PCB	CAS Number	TEF (BGA)	NATO (I-TEF) 1988	WHO 1998 TEF	WHO 2005 TEF	WHO 2022 TEF*
1,2,3,7,8-PeCDF	57117-41-6	0.1	0.05	0.05	0.03	0.01
2,3,4,7,8-PeCDF	57117-31-4	0.1	0.5	0.5	0.3	0.1
1,2,3,4,7,8-HxCDF	70648-26-9	0.1	0.1	0.1	0.1	0.3
1,2,3,6,7,8-HxCDF	57117-44-9	0.1	0.1	0.1	0.1	0.09
1,2,3,7,8,9-HxCDF	72918-21-9	0.1	0.1	0.1	0.1	0.2
2,3,4,6,7,8-HxCDF	60851-34-5	0.1	0.1	0.1	0.1	0.1
1,2,3,4,6,7,8-HpCDF	67562-39-4	0.01	0.01	0.01	0.01	0.02
1,2,3,4,7,8,9-HpCDF	55673-89-7	0.01	0.01	0.01	0.01	0.1
OCDF	39001-02-0	0.001	0.001	0.0001	0.0003	0.002
dl-PCB						
PCB 77	32598-13-3	N/A	N/A	0.0001	0.0001	0.0003
PCB 81	70362-50-4	N/A	N/A	0.0001	0.0003	0.006
PCB 105	32598-14-4	N/A	N/A	0.0001	0.00003	0.00003
PCB 114	74472-37-0	N/A	N/A	0.0005	0.00003	0.00003
PCB 118	31508-00-6	N/A	N/A	0.0001	0.00003	0.00003
PCB 123	65510-44-3	N/A	N/A	0.0001	0.00003	0.00003
PCB 126	57465-28-8	N/A	N/A	0.1	0.1	0.05
PCB 169	32774-16-6	N/A	N/A	0.01	0.03	0.005
PCB 156	38380-08-4	N/A	N/A	0.0005	0.00003	0.00003
PCB 157	69782-90-7	N/A	N/A	0.0005	0.00003	0.00003
PCB 167	52663-72-6	N/A	N/A	0.00001	0.00003	0.00003
PCB 189	39635-31-9	N/A	N/A	0.0001	0.00003	0.00003

*has not yet been incorporated into regulatory requirements

As already mentioned, the 2005 WHO-TEQ concept is currently the standard, but older studies refer to the so-called I-TEQ concept (Tysklind et al., 2024). The TEFs for specific PCDD/Fs and dl-PCBs differ between the various TEF concepts. This makes it difficult to directly compare concentration values from studies using different TEF concepts, which could lead to inconsistencies in the interpretation of the results. However, Tysklind et al. have carried out a comparison of the WHO 2005 TEQ and the I-TEQ concepts for PCDD/Fs and shown that, although there are minor differences in the results, the calculated TEQ values and the conclusions drawn from them are nevertheless fundamentally consistent. Therefore, studies that apply these TEQ concepts can be directly compared with one another (Tysklind et al., 2024).

Use of relevant terms

The literature review conducted as part of this study shows that terms for coarse ash and fly ash are used inconsistently. Terms such as 'fly ash', 'fine ash', 'grate ash' or 'soot' are often used synonymously or with only minor differences, depending on the context or field of study. These differences complicate the comparison and evaluation of studies. Standardised terminology has therefore been used for this project. It is intended to enable clear categorisation and comparison of the results.

Based on the 2009 study by the Bavarian State Office for the Environment, the classification of ash in this project is based on its origin and particle size and comprises the following categories (see also Figure 5):

- **Coarse ash –** Coarse ash refers to ash originating from the grate, combustion chamber or fireplace. It consists mainly of the inorganic, non-combustible components of biomass (Barbarits et al., 2008). It comprises two main components:
  - **Grate ash** – Coarse-grained residue that falls through the grate after combustion.
  - **Combustion chamber ash** – Coarse-grained, partly lumpy residue that remains in the combustion chamber or furnace after combustion.

  Grate ash, combustion chamber ash or a mixture of grate ash and combustion chamber ash is generally referred to as coarse ash, as it is characterised by a larger particle size and a coarser structure ( ). Coarse ash contains larger inorganic components which, due to their higher boiling point and particle size, remain in the residue and are not carried away with the flue gas stream (Barbarits et al., 2008). As grate ash and combustion chamber ash have a comparable chemical composition, separate collection and analysis were not carried out. In the study by the Bavarian State Office for the Environment (2009), this ash is defined as combustion chamber ash.

- **Fly ash** – Fly ash is often colloquially referred to as soot. A distinction is made between:
  - **Sweep ash**[11] – Sweep ash is a fine-grained residue characterised by a high carbon content and low density (also referred to as **fly ash or fine ash**). It is usually black in colour and is swept from the inner wall of the chimney during sweeping and subsequently removed via the inspection flap. Due to its low density, sweep ash leaves the combustion chamber. The portion of fly ash that leaves the flue gas system is referred to as particulate matter after it has exited. If a downstream separator is present, this ash fraction can be retained by a reduction device. If this ash fraction is retained by a cyclone separator, it is described as cyclone ash. In the study by the Bavarian State Office for the Environment (2009), this ash is defined as cyclone ash.
  - **Filter ash**[12] – Filter ash is a fine-grained residue with a high carbon content and low density (also known as **ultrafine fly ash or ultrafine ash**). It is retained in filters located downstream of the heat exchanger. In the case of small combustion plants covered by the 1st BImSchV, these are predominantly electrostatic precipitators. In the case of medium-sized combustion plants covered by the 44th BImSchV, fabric filters or ceramic filters are

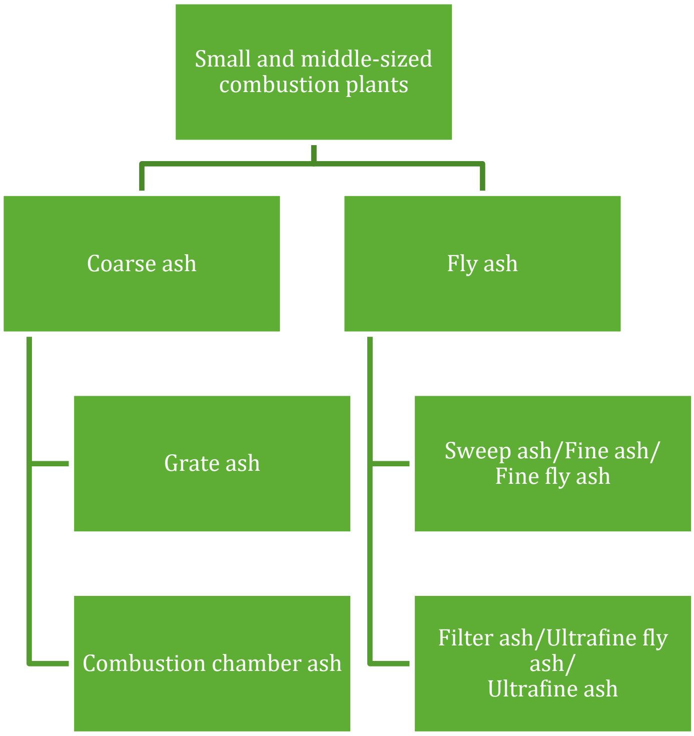
[11] colloquially referred to as soot

[12] colloquially referred to as soot

also used. When this ash escapes from the chimney, it contributes to air pollution and, depending on its size, is classified as particulate matter (PM10, PM2.5, PM1 or PM0.1) in air quality regulations.

This categorisation serves to clearly distinguish between types of ash based on their origin, particle size and physical properties. Unlike coarse ash, fly ash has already left the combustion chamber.

Figure 5: Categories of ash fractions in small combustion plants and medium-sized biomass combustion plants, as defined within the project



Source: Own illustration, Ramboll 2024

According to a 2003 study by the Ministry of the Environment and Transport, BW, between 85 and 95 % of the total ash from the combustion of hardwood, coniferous wood, bark, poplar wood and roadside vegetation, between 85 and 95 % of the total quantity is accounted for by coarse ash (grate ash) and 5–15 % by fine ash (cyclone/filter ash) (Ministry of the Environment and Transport, BW, 2003).

To enable comparison between different studies, the terms used in the literature are assigned to the categories defined in the project. Table 4 shows how frequently used terms from the literature are classified into the project categories.

Table 4: Terms from the literature that are assigned to the terms defined within the project.

Allocation within the project	Term from the literature	Explanation	Source
Coarse ash	Combustion chamber ash	Combustion chamber ash	TLLLR (2020), Pieper (2001)
Coarse ash	Combustion chamber ash	Ash from the combustion chamber	Pieper (2001)

Allocation within the project	Term from the literature	Explanation	Source
Coarse ash	Combustion chamber ash (fine fraction)	Passage from sieving with a mesh size of d = 3.15 mm	Launhardt et al. (1998)
Coarse ash	Combustion chamber ash (coarse fraction)	Residue from sieving with a mesh size of d = 3.15 mm	Launhardt et al. (1998)
Coarse ash	Grate ash	N/A	Ministry for the Environment and Transport, BW (2003)
Fly ash (sweep ash)	Fine ash	Cyclone and ultrafine fly ash	Ministry of the Environment and Transport, BW (2003)
Fly ash (sweep ash)	Fly ash	N/A	Pieper (2001)
Fly ash	Flue gas pipe	N/A	Pieper (2001)
(sweep ash)	Heat exchanger ash (fly ash)	Fly ash from the heat exchanger	Launhardt et al. (1998)
Fly ash	Heat exchanger	N/A	Pieper (2001)
(sweep ash)	Cyclone ash	Ash from the cyclone	TLLLR (2020), Pieper (2001)
Fly ash	Chimney soot	N/A	Dumler-Gradl et al. (1995)
(sweep ash)	Chimney soot (fine fly ash)	Chimney soot/fine fly ash from the cleaned section of the chimney	Launhardt et al. (1998)
Fly ash (filter ash)	Filter ash	Ash from the filter, such as fabric filters	TLLLR (2020)

When discussing results, the original term from the literature is cited and supplemented with the corresponding classification within the project. This approach is intended to ensure traceability and transparency.

Results of the literature review

2.3.1 Small combustion plants

The concentrations of PCDD/Fs and dl-PCBs in bottom ash and fly ash have been investigated in various studies. These studies provide important information on the distribution and effects of PCDD/Fs and dl-PCBs in combustion residues such as ash and soot. The following chapters present the most important studies and their results regarding PCDD/F and dl-PCB levels in various types of bottom ash and fly ash.

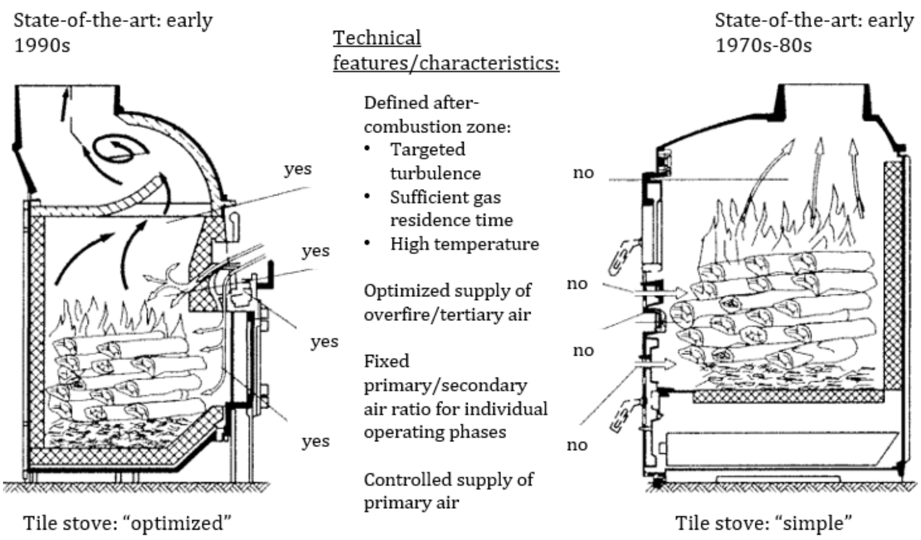
2.3.1.1 Domestic heating systems

The available literature on the concentrations of PCDD/Fs and dl-PCBs in bottom ash and fly ash from single-room combustion systems in Germany is limited. During the literature review for this project, three studies (Launhardt et al., 1998, Dumler-Gradl et al., 1995, Thoma, 1998) were found that provide relevant information on single-room combustion systems within the scope of this investigation. However, these studies dealt exclusively with PCDD/Fs and contain no data on dl-PCB levels. The relevant information from this study is listed in Appendix A.1 (seeTable 31).

Coarse ash

A study by Launhardt et al. examined various ash samples collected during the combustion tests. Samples from the combustion chamber, the heat exchanger and chimney soot from the cleaned area[13] were analysed. As explained in the study, the majority of the combustion residue remains as coarse ash, which accounted for 83–93 % of the total quantity in the combustion tests. Furthermore, the study distinguishes between the coarse and fine fractions of the combustion chamber ash. The coarse fraction, which was separated by sieving, accounted for 50–70 % of the combustion chamber ash and consisted mainly of unburned fuel residues. The fine fraction, on the other hand, consisted largely of mineral residues of the burnt fuel. The concentrations of PCDD/Fs found in the fine fraction of the coarse ash ranged between 0.8 ng/kg I-TEQ and 75 ng/kg I-TEQ, with ash samples from coniferous wood, particularly in log form, generally exhibiting the highest PCDD/F content (Launhardt et al., 1998). The study examined two different systems: 'simple' and 'optimised'. As defined in the study, an 'optimised' stove refers to a tiled stove equipped with the following technical features: defined after-combustion zone (targeted turbulence, sufficient gas residence time, high temperature), optimised supply of 'upper draught'[14] , fixed primary/secondary air ratio for individual operating phases, and precisely metered supply of primary air (Launhardt et al., 1998). A 'simple' tiled stove does not possess these technical features (see Figure 6).

Figure 6: Combustion characteristics of the tiled stoves examined



Source: Launhardt et al., 1998. Translated by Ramboll.

A comparison of these two different tiled stoves showed that the ash from the "optimised" system contained less PCDD/Fs than that from the "simple" system. In contrast to the fine fraction, almost no PCDD/Fs were found in the coarse fraction of the combustion chamber ash from either tiled stove. The concentrations in these samples ranged between 0.6 ng/kg I-TEQ

[13] A 'chimney' is a predominantly vertical flue pipe specifically designed to safely conduct exhaust and flue gases from a fireplace out into the open air via the roof. The term 'fireplace' refers to the hearth itself. However, the term 'fireplace' is often used synonymously with the term 'chimney'. In this report, these terms are used in their literal sense, unless they originate from, or relate to, the underlying literature, as is the case here with Launhardt et al., 1998. In that work, the term 'fireplace' is used to refer to the actual chimney. The intended meaning is clear from the context in each instance.

[14] The term "upper air" refers to secondary air supplied above the fuel, as opposed to primary air, which is supplied from below. Secondary air is intended to improve after-combustion in the upper part of the flame.

and 1.2 ng/kg I-TEQ, which was close to the detection limit of the analytical method. The highest PCDD/F content of 75 ng/kg I-TEQ was measured in the fine fraction of the combustion chamber ash from a simple tiled stove (Launhardt et al., 1998).

Sweep ash

According to the study by Launhardt et al., only a small proportion of the combustion residues escapes from the combustion chamber with the flue gases. Some of these residues are deposited as fly ash and fine fly ash on the inner walls of the heat exchanger and the chimney. However, the finest particles are transported into the environment with the flue gases. In the systems investigated by Launhardt et al., ash particles in the flue gas accounted for 7 to 17 % of the total residue. The heat exchanger helps to reduce the dust content in the flue gases due to its ability to retain ash particles. Chimney soot accounted for 2 to 4 % of the residue, whilst heat exchanger ash (fly ash generated in the heat exchanger) ranged from 0.8 to 8 % (Launhardt et al., 1998).

The PCDD/F concentrations in the fly ash from the heat exchanger and in the chimney soot examined are summarised as 'sweep ash' inTable 31 . According to Launhardt et al., low concentrations of PCDD/Fs (average of 6.5 ng I-TEQ/kg DM) were found in the fly ash from the heat exchanger. The average PCDD/F values detected in chimney soot (7.9 ng I-TEQ/kg DM) were only slightly higher (Launhardt et al., 1998). The PCDD/F concentrations determined by Launhardt et al. are significantly lower than those observed by Dumler-Gradl et al.

In a Bavaria-wide study in 1986, Dumler-Gradl et al. found average values of 3,454 ng I-TEQ/kg DM PCDD/F in the soot from tiled stoves and 2,105 ng I-TEQ/kg DM PCDD/F in the soot from single stoves (Dumler-Gradl et al., 1995). In another study, significantly higher concentrations of PCDD/F I-TEQ (up to 48,240 ng/kg I-TEQ) were found in chimney soot (Thoma, 1988). However, there is no information on the type of wood used in the samples, which were taken from domestic heating systems.

According to Launhardt et al., the PCDD/F contamination of ash from the combustion chamber depends heavily on the type of fuel. Whilst the PCDD/F concentrations in the fine fractions of combustion chamber ash from beech wood combustion remained ≤20 ng/kg I-TEQ, average PCDD/F concentrations of up to 75 ng/kg I-TEQ were measured during the combustion of coniferous wood. The temperature profiles in the combustion chamber showed that PCDD/Fs are formed during de novo synthesis in the final cooling phase, which begins after several combustion cycles. In this phase, the embers cool down, favouring PCDD/F formation. Unburned charcoal, which was sieved out of the combustion chamber ash as a coarse fraction, had, by contrast, very low PCDD/F concentrations (Launhardt et al., 1998).

Conclusion

The results of the literature review allow the following conclusions to be drawn:

PCDD/F levels vary depending on the type of combustion plant, the fuel used and the ash fraction. In coarse ash from single-chamber combustion plants, PCDD/F levels are generally relatively low (<100 ng I-TEQ/kg).

In fly ash, however, the PCDD/F concentrations are significantly higher and can reach several thousand ng I-TEQ/kg. In some studies, high values of over 10,000 ng I-TEQ/kg have been measured. This is partly due to the fact that the very small soot particles provide a very large surface area onto which PCDD/Fs formed during combustion can adsorb.

The type of wood also influences the PCDD/F levels in the ash. For coniferous wood, the levels reported in the identified literature are generally higher in the ash than for deciduous wood.

2.3.1.2 Solid fuel boilers

In contrast to the available literature on single-room combustion systems, more studies were found in the field of solid fuel boilers that contain information on PCDD/F and dl-PCB concentrations in ash and soot.

Coarse ash

According to the literature, PCDD/F concentrations in furnace ash are low when burning untreated softwood and hardwood in most solid fuel boilers, particularly those equipped with multicyclones or fabric filters. For example, the combustion of hardwood in various solid fuel boilers resulted in PCDD/F concentrations ranging from <2 ng I-TEQ/kg in coarse ash from wood chip boilers (Baden-Württemberg Ministry of the Environment and Transport, BW, 2003) to 4.3 ng I-TEQ/kg in coarse ash from log-fired boilers (Launhardt et al., 1998). In contrast, PCDD/F concentrations from the combustion of untreated softwood in furnace ash were significantly higher, ranging from <2 ng I-TEQ/kg in coarse ash from wood chip boilers to 310 ng I-TEQ/kg in coarse ash from log boilers (Baden-Württemberg Ministry of the Environment and Transport, BW, 2003; Launhardt et al., 1998). It is noteworthy that smaller systems with exhaust gas blowers and microprocessor-controlled air regulation result in very low PCDD/F concentrations in the coarse fraction of the ash from log-fired boilers (0.9–1.6 ng I-TEQ/kg), but significantly higher concentrations in the fine fraction of coarse ash from log-fired boilers, which can reach up to 310 ng I-TEQ/kg (Launhardt et al., 1998). This shows that finer particles tend to bind more pollutants.

Studies show that cyclone-based systems generally exhibit lower concentrations of PCDD/Fs and PCBs in bottom ash, some of which are below the limit of detection (Ministry of the Environment and Transport, BW, 2003; TLLR 2020). The study by the Ministry of the Environment and Transport shows, for example, that PCDD/F levels in grate ash from the combustion of untreated wood are below 2 ng I-TEQ/kg (Ministry of the Environment and Transport, BW, 2003).

Higher PCDD/F concentrations have been reported in combustion chamber ash from the burning of treated wood (e.g. chipboard treated with sulphate or chloride), with values ranging between 175 and 187 ng I-TEQ/kg (Pieper, A., 2001). PCDD/F concentrations in combustion chamber ash have also been measured during the combustion of other biomass such as grain, straw and roadside vegetation. For example, PCDD/F and dl-PCB concentrations from grain combustion ranged between 3 and 46 ng WHO_{2005} TEQ/kg in coarse ash from pellet boilers (TLLLR, 2020), and from straw combustion between <1 ng WHO_{2005} TEQ/kg in coarse ash from a plant where round bales and square bales are incinerated (TLLLR, 2020) and 33 ng I-TEQ/kg DM in coarse ash from a plant where pelletised wheat straw is incinerated (Launhardt et al., 2000). For roadside vegetation, the values were low (<2 ng I-TEQ PCDD/F/kg and <0.02 mg PCB/kg ash) (Ministry of the Environment and Transport, BW, 2003). These results indicate that the combustion of such biomass does not lead to increased PCDD/F and PCB levels in the bottom ash.

When burning mixed coniferous wood at 30 % heating load, PCDD/F concentrations of up to 68.1 ng I-TEQ/kg were measured in combustion chamber ash (Pieper, 2001). At 100 % heating load, however, the values fell significantly under optimised conditions to a range of 0.006–0.038 ng I-TEQ/kg (Pieper, 2001).

Sweep ash

With regard to boiler ash, untreated wood exhibits a wide range of PCDD/F concentrations, which depend heavily on the solid fuel boiler.

When burning untreated hardwood, PCDD/F concentrations ranged from 25 ng I-TEQ/kg in ash from log-fired boilers (Launhardt et al., 1998) to 896 ng I-TEQ/kg in bottom ash from wood chip boilers (Ministry of the Environment and Transport, BW, 2003). Higher concentrations were found in the fine ash from wood chip boilers in experiments with cyclone filters, in particular 506 ng I-TEQ/kg when using poplar wood and 896 ng I-TEQ/kg for other hardwood species that are not further defined (Ministry of the Environment and Transport, BW, 2003).

Untreated coniferous wood shows slightly lower concentrations, ranging from 23 ng I-TEQ/kg in heat exchanger ash (Launhardt et al., 2000) to 1,577 ng I-TEQ/kg in the fine ash from wood chip boilers (Ministry of the Environment and Transport, BW, 2003). For example, PCDD/F concentrations in fly ash from heat exchangers ranged from 23–53 ng I-TEQ/kg when chopped spruce was burned (Launhardt et al., 2000). When mixed coniferous wood was burned, PCDD/F concentrations reached up to 117 ng I-TEQ/kg in fly ash (Pieper, 2001) and 1,577 ng I-TEQ/kg in fine ash from wood chip boilers using other, unspecified hardwood species (Baden-Württemberg Ministry of the Environment and Transport, BW, 2003).

In the case of treated wood, such as chipboard hardened with sulphate/chloride, very different PCDD/F concentrations were measured in fly ash, ranging from 28.5 to 515 ng I-TEQ/kg depending on the heating load (Pieper, 2001). The combustion of mixed wood, such as untreated chopped spruce wood together with chemically treated wood in a 3:1 ratio, results in moderate to high PCDD/F concentrations (300–743 ng I-TEQ/kg) in fly ash (Pieper, 2001).

Fly ash from the combustion of cereals (e.g. triticale) in water-cooled combustion chambers showed moderate PCDD/F concentrations of 401 ng I-TEQ/kg at 100 % heating load (Launhardt et al., 2000). The combustion of straw leads to highly variable PCDD/F concentrations, depending on the load and conditions. For example, the combustion of chopped straw resulted in PCDD/F concentrations in the heat exchanger ash of 1,129 ng I-TEQ/kg at full load (Launhardt et al., 2000). Concentrations in the chimney soot were even higher (1,691 ng I-TEQ/kg) (Launhardt et al., 2000). When burning pelletised straw, a PCDD/F concentration of 860 ng I-TEQ/kg was measured at full load, but this rose to 5,382 ng I-TEQ/kg at partial load (Launhardt et al., 2000). Rapeseed meal and chopped hay resulted in PCDD/F concentrations of 715 ng I-TEQ/kg and 3,796 ng I-TEQ/kg respectively in the fly ash (Launhardt et al., 2000).

Filter ash

Filter ash from the combustion of untreated wood generally shows relatively low PCDD/F concentrations. For example, the combustion of untreated wood chips resulted in PCDD/F concentrations of 91 ng TEQ/kg DM (WHO $_{2005}$) (TLLLR, 2020). The combustion of grain showed a wide range of PCDD/F concentrations in the filter ash. In slightly larger systems (0.95 MW) that use grain as fuel and are equipped with a combination of a multicyclone and a fabric filter, PCDD/F and dl-PCB concentrations ranged between 67 and 271 ng TEQ/kg DM (WHO $_{2005}$) (TLLLR, 2020). Other biomass fuels, such as hay and mixed biomass (e.g. hay, reed and wood), also showed comparatively high PCDD/F concentrations. A mixed biomass fuel consisting of 75 % hay, 10 % reed and 15 % wood yielded PCDD/F and dl-PCB concentrations of 168 to 2,100 ng TEQ/kg DM (WHO_{2005}) in filter ash from systems with multicyclones and fabric filters (TLLLR, 2020).

Conclusion

Overall, the literature review on solid fuel boilers shows that PCDD/F levels in ash and soot depend on the type of fuel and the combustion technology.

In coarse ash, PCDD/F levels are generally relatively low (<100 ng I-TEQ/kg), particularly when burning untreated wood. This means that larger ash particles tend to contain low levels of these pollutants.

In the fine fraction of coarse ash, however, the levels can be significantly higher, with values reaching up to several hundred ng I-TEQ/kg. This is because the finer ash particles provide a larger surface area onto which PCDD/Fs can adsorb.

As the heating load increases (i.e. the higher the combustion intensity), the PCDD/F levels in the ash decrease. This can be explained by the fact that at higher combustion temperatures and energy levels, the formation or deposition of PCDD/Fs in the ash is reduced, and chlorinated organic compounds are also destroyed. Consequently, ash from combustion processes with a higher heating load is less contaminated than that from processes with a lower heating load.

In sweep ash, PCDD/F levels are generally moderate (<1,000 ng I-TEQ/kg). In individual cases, levels may also exceed 1,000 ng I-TEQ/kg. Interestingly, when burning biomass other than wood, such as straw, higher values are sometimes found, which can even reach several 1,000 ng I-TEQ/kg. This shows that the fuel used has an influence on the PCDD/F levels in the ash.

It can generally be observed that PCDD/F levels increase with the fineness of the ash. This means that the highest levels of PCDD/Fs are to be expected in filter ash, the finest ash fraction, and the lowest levels in combustion chamber ash.

Selected information from the literature review is summarised in Appendix A.2 (see Table 32).

2.3.1.3 Boilers in wood-processing and woodworking businesses

In accordance with the 1st Federal Immission Control Ordinance (1.BImSchV), certain fuels listed in Article 3(1)(6) or (7) may only be used in combustion plants with a rated thermal input of 30 kilowatts or more and exclusively in woodworking or wood processing businesses. The relevant information in this regard that was identified as part of this project is summarised in Appendix A.4 (see Table 34).

In particular, this concerns the following fuels:

"6. painted, varnished or coated wood and any resulting residues, provided that no wood preservatives have been applied or are present as a result of treatment, and that coatings do not contain any organohalogen compounds or heavy metals,

7. plywood, chipboard, fibreboard or other glued wood, as well as waste arising therefrom, provided that no wood preservatives have been applied or are present as a result of treatment, and coatings do not contain halogenated organic compounds or heavy metals[15]"

As higher concentrations of PCDD/Fs and dl-PCBs are to be expected during the combustion of these fuels, this project also covers the woodworking industry, which encompasses both commercial and domestic combustion systems (e.g. dwellings supplied via a communal heating system from the commercial sector).

However, information on PCDD/F and dl-PCB concentrations in coarse and fly ash from the wood-processing industry in Germany is very limited. During the literature review, only one study by Pohland et al. from 1994 was identified. Relevant information from this study is listed in Table 34 in Appendix A.4. In the study, samples were taken from five different plants in the wood-processing industry. According to the results, the concentrations of PCDD/Fs in grate ash are significantly lower than in fly ash. The PCDD/F levels in coarse ash are very low (< 1 ng/kg TEQ BGA), and those in bottom ash are also low (< 1,000 ng/kg TEQ BGA) (Pohland et al., 1994).

[15] English translation is provided for the purpose of this study. For legal interpretation and application, the German law (1. BImSchV) shall prevail.

2.3.2 Medium-sized biomass combustion plants

The information presented here on PCDD/Fs and dl-PCBs from medium-sized biomass combustion plants in Germany is based primarily on two comprehensive studies. The relevant information from these studies is summarised in Annex A.3 (see Table 33).

One of the studies examined various plants (Ministry of the Environment and Transport, BW, 2003). These plants were selected at random from the existing plant stock in Baden-Württemberg, based on specific criteria. The plants examined, which fall into the category of medium-sized combustion plants, varied in size and capacity. They ranged from grate-fired plants with a thermal capacity of 1 MW to grate-fired plants larger than 20 MW, which are used to produce electricity and heat from Category A II waste wood in accordance with the Waste Wood Ordinance. The study analysed fuels such as untreated waste wood A I, municipal wood chips, roadside vegetation, hardwood, softwood, spruce bark, pine bark and waste wood A II. In this study, the entire group of PCBs was analysed, not just dl-PCBs (Ministry of the Environment and Transport, BW, 2003).

The other study, published by the Thuringian State Office for Agriculture and Rural Areas in 2020, examined biomass ash produced in heating (and power) plants during the mono-combustion of natural plant-based fuels. In addition to straw and landscape management hay as herbaceous fuels, wood chips from forestry and landscape management wood were also used in these plants. To this end, a Germany-wide monitoring programme was carried out on eleven existing biomass conversion plants and their combustion residues. Of the eleven biomass combustion plants analysed, two meet the definition of medium-sized biomass combustion plants, which are also being investigated as part of this project (TLLLR, 2020).

The concentrations of PCDD/Fs and dl-PCBs from the studies conducted are listed in Table 33. As shown there, dioxin concentrations in coarse ash are comparatively low, particularly in untreated wood fuels (e.g. hardwood, softwood and Category A I wood residues). However, significant variations in PCDD/F concentrations were observed in sweep ash, depending on the fuel type and the combustion system. Whilst ash from the combustion of untreated wood fuels exhibits low toxicity values (<1 ng TEQ/kg), the combustion of treated wood leads to higher values, which underscores the influence of fuel composition on the formation of PCDD/Fs and dl-PCBs.

Conclusion

Overall, dioxin concentrations in medium-sized combustion plants appear to be generally lower than in small combustion plants. Medium-sized plants typically have better-controlled combustion and flue gas cleaning, such as electrostatic precipitators or fabric filters, which reduce the formation of PCDD/Fs and dl-PCBs or improve the retention of particles. In contrast, small plants often lack such advanced features, leading to incomplete combustion and higher formation of PCDD/Fs and dl-PCBs.

3 Selection of relevant plants in Germany, sampling and analysis

As part of the data collection on PCDD/PCDF and dl-PCB concentrations in ash from German smal combustion plants and medium-sized biomass combustion plants, sampling was carried out at 20 small combustion plants and 10 medium-sized biomass combustion plants, in addition to a literature review. The ash samples were analysed in the laboratory for PCDD/PCDF, dl-PCBs and chlorine. The results were subsequently incorporated into the evaluation of the literature review.

3.1 Small combustion plants

The focus of this study is on small combustion plants, which are regulated by the First Ordinance Implementing the Federal Immission Control Act (1. BImSchV). The study primarily addresses private households, with a particular focus on log wood, wood chips and wood pellets used in stoves and boilers. Furthermore, small combustion plants in the woodworking and wood-processing industries (e.g. joinery workshops) are of interest, as increased PCDD/F-emissions are suspected in these facilities. Confirmation of this suspicion would potentially underscore the need for further investigations in this sector. Sampling was carried out on both single-room combustion systems and solid fuel boilers, with the focus on solid fuel boilers, as higher PCDD/F emissions were expected from these. In total, 20 samples were taken from the combustion chamber (grate and combustion chamber; coarse ash, grate ash) as well as from the base of the chimney and the connection to the chimney (fly ash) from 20 small combustion plants. The selection and sampling of the small combustion plants was supported by the Central Guild Association of Chimney Sweeps (ZIV).

3.1.1 Selection

When selecting the 20 small combustion plants, care was taken to ensure that they reflected as broad and typical a selection as possible of the plant stock in Germany.

The following criteria were taken into account:

- Type of combustion plant (wood-burning stove, pellet stove, tiled stove, cooker, log-fired boiler, pellet boiler, wood chip boiler),
- Rated heat output,
- Date of installation/date of type approval/BImSchV stage (before 22 March 2010, from 22 March 2010 to 31 December 2014 (Stage 1), after 31 December 2014 (Stage 2)),
- Fuel (fuels in accordance with Section 3 of the 1st BImSchV; logs, wood pellets, wood chips, etc.),
- Residue (coarse ash, fly ash),
- Regional distribution (North, East, South, West).

A total of 6 single-room combustion systems and 14 solid fuel boilers from various regions of Germany (5 systems each in the West, South, East and North) were sampled. The selection is shown in Table 5, Table 6 and Table 7.

Table 5: Single-room combustion systems with a rated output of 4.5 to 10 kW (6 systems)

Commissioning	Wood-burning stove*	Wood-burning stove with dust separator*	Pellet stove**	Tiled stove*	Cooker/ Heating stove*
before 22 March 2010					
from 22 March 2010 to 31 December 2014 (Stage 1)	X			X	
after 31 December 2014 (Stage 2)	X	X	X		X

* Fuel No. 4, ** Fuel No. 5a (in each case in accordance with 1st BImSchV, Section 3)

Table 6: Solid fuel boilers with a rated output of 10 to 38 kW (7 systems)

Commissioning	Log-fired boiler*	Log-fired boiler with dust separator*	Pellet boiler**	Pellet boiler with dust separator**	Pellet boiler with condensing technology**
before 22 March 2010	X				
from 22 March 2010 to 31 December 2014 (Stage 1)	X		X		
after 31 December 2014 (Phase 2)		X	X	X	X

* Fuel No. 4, ** Fuel No. 5a (in each case in accordance with 1st BImSchV, Section 3)

Table 7: Solid fuel boilers with a rated output of 30 to 100 kW (7 systems)

Commissioning	Wood chip boiler*	Wood chip boilers with dust separators*	Boilers (woodworking and wood-processing industries)**	Boiler (woodworking and wood-processing industries) with dust separator**
before 22 March 2010 (Stage 0)	X		X	
from 22 March 2010 to 31 December 2014 (Stage 1)	X		X	
after 31 December 2014 (Phase 2)	X	X		X

* Fuel No. 4; ** Fuels 6/7 (in each case in accordance with 1st BImSchV, Section 3)

Originally, for the sake of representativeness among single-room combustion systems, a wood-burning stove with a downstream dust separator, which was commissioned before 22 March 2010, was selected. As no such system could be identified, a wood-burning stove with a downstream dust separator, which was commissioned after 31 December 2014, was included in the selection instead. For the sampling, it was important to collect a sufficiently large quantity of ash. This proved to be a challenge in retrospect for some combustion systems. This concerns pellet-burning appliances, which produce very small amounts of ash due to their mode of operation and combustion technology[16].

3.1.2 Sampling procedure

The ZIV was responsible for identifying the individual plants to be sampled and for taking the bottom ash and fly ash samples; to this end, four chimney sweeps from different districts received a brief briefing from Ramboll. To this end, Ramboll drew up a document outlining the sampling procedure (see Annex B.1), a sampling protocol (see Annex B.2) and a laboratory order, and coordinated these with the Federal Environment Agency. Sampling was carried out in accordance with LAGA PN 98[17] between February and April 2025. Samples for coarse ash were taken from the grate and the combustion chamber. Samples for fly ash were taken from the connection between the combustion chamber and the chimney, as well as from the inspection flap in the chimney. Sampling was carried out using a suitable sampling device (usually a stainless steel trowel) in accordance with LAGA PN 98, following the sampling procedure document. During this process, the condition of the combustion plant was checked and relevant metadata was recorded in the sampling log.

In most systems, there was a sufficient quantity of ash, and as a rule, all the ash was collected and subsequently processed in the laboratory. In two systems (a wood-burning stove and a pellet stove), the quantity of fly ash present was very small, so it was not certain whether this would be sufficient for analysis.

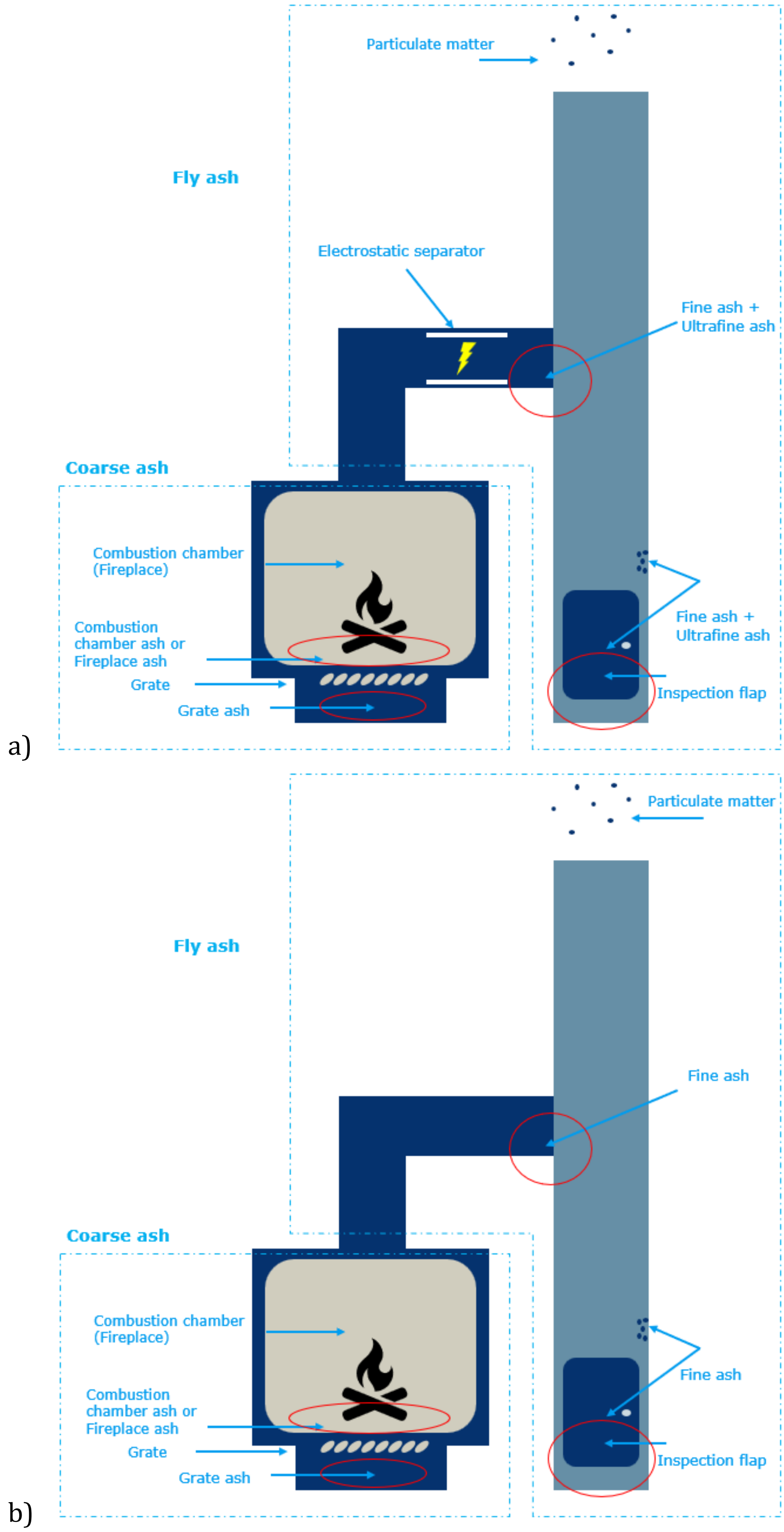
The samples were then sent to the laboratory of Eurofins GfA Lab Service GmbH.

Figure 7 shows two simplified diagrams of small combustion plants, one with and one without a downstream electrostatic precipitator. The ash sampling points (combustion chamber, connection between the combustion chamber and the flue, and inspection flap) are marked accordingly.

[16] Information from discussions with ZIV

[17] Guideline on the procedure for physical, chemical and biological analyses in connection with the recovery/disposal of waste

Figure 7: Sketch of a small combustion plant: a) with and b) without an electrostatic precipitator. The ash sampling points are marked with a red circle in each case.



Source: Own illustration, Ramboll 2025

3.2 Medium-sized combustion plants

The focus of this study is on medium-sized combustion plants, which are regulated under the 44th Ordinance for the Implementation of the Federal Immission Control Act (44th BImSchV) and use biomass as fuel. A total of ten fly ash samples were taken from ten biomass combustion plants and analysed.

3.2.1 Selection

When selecting the biomass combustion plants to be sampled, criteria were initially established for the entire plant fleet in Germany:

- Thermal capacity of the plant in MW (1–5 MW, 5–20 MW, 20–50 MW)
- Date of commissioning (existing or new plant in accordance with 44th BImSchV)
- For existing plants, also the date of installation of a filter or electrostatic precipitator before or after 20 June 2019
- Fuel types (wood pellets, wood chips, wood from landscape maintenance, production residues (solid wood, chipboard, etc.), waste wood A I, waste wood A II, straw, grain, etc.)
- Type of plant (heating boiler, steam boiler, combined heat and power, etc.)
- Type of dust collector (fabric filter, electrostatic precipitator, etc.)
- Regional distribution
- Sector (downstream)

The aim was to specifically include plants where higher PCDD/PCDF levels in the ash were to be expected – such as those using waste wood A II, chipboard or grain as fuel. Against this background, the selected plants do not constitute a representative sample.

The Federal Environment Agency then contacted the competent authorities in the federal states, informed them about the project and requested their assistance in selecting and contacting suitable plants. To this end, a plant profile was drawn up (see Annex C.1) and sent to the competent authorities with a request that they have it completed by interested plant operators.

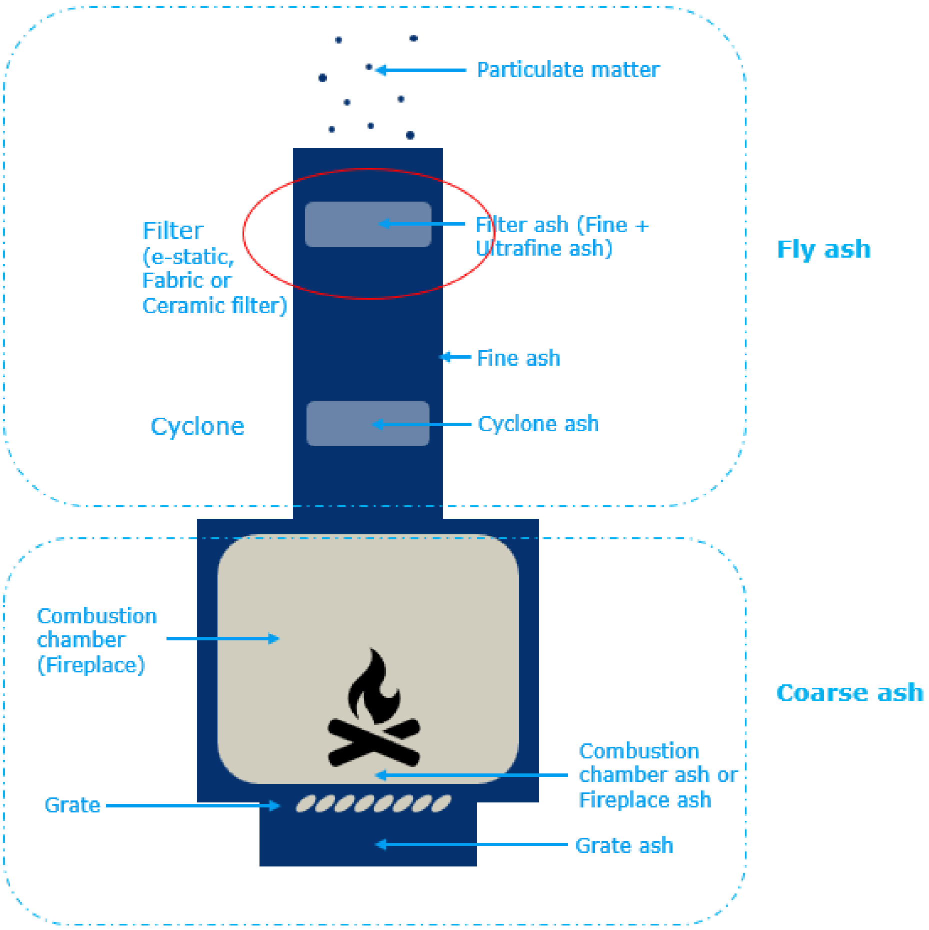
In response to the request, representatives from five federal states proposed a total of 14 plants, two of which had not yet been built at the time of sampling. Following consultation with the Federal Environment Agency and the relevant state authorities, nine of the proposed plants remained relevant for sampling, and the plant operators were willing to support the project. At one plant, two different boilers were in operation. Two different samples were taken there (see Table 8). Thus, ten samples were taken from the nine available plants, even though not all of the above-mentioned representativeness criteria were met.

3.2.2 Sampling procedure

Following discussions between the project team, the Federal Environment Agency and the relevant state authorities, the project team contacted the operators of the available facilities, discussed the on-site conditions and arranged dates for sampling. Sampling of the plants took place in March. The samplers from Ramboll, certified in accordance with LAGA PN 98, were each accompanied by a local contact person who introduced and explained the plant to them, including the biomass used and the resulting ash output. The filter ash samples were taken using a stainless steel hand shovel from the ash collection or storage containers behind the various filters, in accordance with LAGA PN 98 and the sampling procedure document (see Annex B.1). During this process, the condition of the combustion plant was checked and relevant metadata recorded in the sampling log. In some cases, the metadata had already been requested earlier on the basis of the sampling protocol, and for many plants it was supplied retrospectively following the sampling in April. No inhomogeneities were detected in the filter ash to be sampled during the sampling process. Depending on local conditions at the sampling sites, a composite sample was obtained using a fractionating scoop or created from several individual samples, and this was subsequently further processed in the laboratory. The sampling protocol for medium-sized biomass combustion plants can be found in Annex C.2. The samples were then sent to the laboratory of Eurofins GfA Lab Service GmbH.

Figure 8 shows a simplified diagram of a medium-sized combustion plant. The ash sampling point is marked accordingly.

Figure 8: Sketch of a medium-sized combustion plant. The ash sampling point is marked with a red circle.



Source: Own illustration, Ramboll 2025

Table 8: Medium-sized biomass combustion plant

	P1**	P10**	P2	P3	P4	P5	P6	P7	P8	P9
	A	A	B	C	D	E	F	G	H	I
Commissioning after 2018	No	No	No	No	No	Yes	No	No	No	No
Power (MW)	5	4.5	6.7 (2.4 + 4.3)	2.5	8.7	1.225	0.275	4.6	13.38 (4.88 + 8.5)	2
Filter*	EP	EP	EP	EP	FF	CF	FF	FF	EP	EP
Raw materials****	Landscape manageme nt timber	Landscape manageme nt timber	A II	A II	A II	A II, A I, untreated timber	Cereals	A I, A II	Production residues (beech sawdust, bark)	A I, A II, untreated wood
System type	Thermal oil boiler***	Hot water boiler	Hot water boiler + Thermal oil boiler	Hot water boiler	Hot water boiler	Hot water boiler	Hot water boiler	Hot water boiler	Hot water boiler	Hot water boiler
Industry	Energy generation	Energy generation	Furniture	Furniture	Furniture	Waste manageme nt	Agriculture	Heat supply	Wood processing	Heat generation

*EP=Electrostatic precipitator, FF=Fabric filter, CF=Ceramic filter

**P1 and P10 are two different boilers in the same combustion plant

***was shut down due to a faulty heat exchanger. It was switched on specifically for the sampling. The sample also contains fly ash from the hot water boiler (P10)

****A I – Waste wood category A I, A II – Waste wood category A II

3.3 Sample analysis methods used

To determine the chlorine, PCDD/F and dl-PCB contents, the samples were sent to the laboratory by the samplers (chimney sweeps or project team).

In the first step, all samples were prepared and homogenised. The dry matter was then determined, and finally the concentrations of PCDD/Fs, dl-PCBs and chlorine were quantified. Sampling the ash for chlorine serves as an indication of potentially high concentrations of PCDD/Fs and dl-PCBs.

3.3.1 Sample preparation and homogenisation

Depending on the nature of the sample material, pre-crushing may first be necessary to prepare the sample for further processing. Homogenisation then takes place using a suitable grinding method, for example by using a cutting mill, knife mill, ball mill or cryogenic grinding. The choice of grinding technique depends on the specific matrix of the sample in order to achieve a homogenised matrix.

3.3.2 Dry matter

To determine the dry weight, the sample material is subjected to gravimetric analysis. This involves recording the mass of the sample before and after the drying process. The difference between the two values provides information on the moisture content and enables the dry weight to be determined. An internally validated method at the laboratory, developed specifically for ash-containing materials, serves as a reference.

3.3.3 PCDD/Fs and dl-PCBs

The laboratory carrying out the analysis is accredited for the determination of persistent organic pollutants (POPs) such as polychlorinated dibenzodioxins and furans (PCDD/Fs) and polychlorinated biphenyls (PCBs) in accordance with DIN EN ISO/IEC 17025:2018.

For the analysis of PCDD/Fs and dl-PCBs, the sample is first ground with a mixture of polyacrylic acid and sodium sulphate to create a homogeneous matrix for further processing. Subsequently, all PCDD/F and dl-PCB congeners to be determined are added in the form of internally standardised, $^{13}C_{12}$-labelled reference substances. The analytes are then extracted using a Soxhlet procedure.

After extraction, the crude extract is purified by column chromatography (clean-up) to remove interfering matrix components. Prior to the actual analysis, further ^{13}C-labelled internal standards are added to enable the recovery rates to be monitored and evaluated during the procedure.

The determination of PCDD/F and dl-PCB congeners is finally carried out using gas chromatography coupled with a tandem mass spectrometer (GC-MS/MS). Quantification is based on the isotope dilution method, in which the concentrations of the native congeners are determined by comparison with the added ^{13}C-labelled standards. The results are reported as total TEQ, taking into account the WHO TEQ factors from 2005. An internally validated method serves as the reference procedure.

The method’s performance data, including the limit of quantification, are shown in Table 9.

Table 9: Characteristics of the method

Parameter group	Parameter	Limit of quantification, ng/kg DM	Expanded measurement uncertainty (k=2), %
PCDD/Fs	2,3,7,8-TetraCDD	0.18	30
	1,2,3,7,8-PentaCDD	0.24	30
	1,2,3,4,7,8-HexaCDD	0.48	30
	1,2,3,6,7,8-HexaCDD	0.48	30
	1,2,3,7,8,9-HexaCDD	0.48	30
	1,2,3,4,6,7,8-HeptaCDD	0.54	30
	OctaCDD	2.20	30
	2,3,7,8-TetraCDF	0.32	30
	1,2,3,7,8-PentaCDF	0.44	30
	2,3,4,7,8-PentaCDF	0.44	30
	1,2,3,4,7,8-HexaCDF	0.40	30
	1,2,3,6,7,8-HexaCDF	0.40	30
	1,2,3,7,8,9-HexaCDF	0.40	30
	2,3,4,6,7,8-HexaCDF	0.40	30
	1,2,3,4,6,7,8-HeptaCDF	0.52	30
	1,2,3,4,7,8,9-HeptaCDF	0.38	30
	OctaCDF	2.20	30
	WHO (2005) – PCDD/F-TEQ excl. LOQ	ND	–
	WHO (2005) – PCDD/F-TEQ incl. LOQ	1.01	30
dl-PCBs	PCB 77	3.60	30
	PCB 81	0.78	30
	PCB 105	7.80	30
	PCB 114	0.94	30
	PCB 118	28.00	30
	PCB 123	0.80	30
	PCB 126	1.02	30
	PCB 156	4.40	30
	PCB 157	0.90	30
	PCB 167	2.20	30
	PCB 169	2.40	30

Parameter group	Parameter	Limit of quantification, ng/kg DM	Expanded measurement uncertainty (k=2), %
	PCB 189	0.80	30
	WHO (2005) PCB-TEQ excl. LOQ	ND	–
	WHO (2005) PCB-TEQ incl. LOQ	0.13	30
Total PCDD/F and dl-PCB (WHO-TEQ)	WHO (2005) TEQ excluding LOQ	ND	–
	WHO (2005) TEQ incl. LOQ	1.15	30

ND – not determined, as none of the relevant congeners exceed the LOQ

3.3.4 Chlorine content

The total chlorine content is determined in accordance with the reference method specified in DIN 51727:2011-11, Method B. This involves a combination of ion chromatography with electrochemical detection (IC-ED).

The limit of quantification is 50 mg/kg.

4 Analysis of the results

4.1 Results of the laboratory analysis

The samples were analysed for PCDD/Fs, dl-PCBs and total chlorine at the Eurofins GfA Lab Service GmbH laboratory.

In a total of two samples, there was insufficient ash to carry out the analysis of PCDD/Fs and dl-PCBs. These were the fly ash from the single-chamber combustion plant P03 and the solid fuel boiler P13. For eight out of ten samples from the medium-sized biomass combustion plants, the analysis of the total chlorine content could not be carried out for logistical reasons.

All results are presented in the following sections.

4.1.1 Small combustion plants

4.1.1.1 Single-room combustion systems

A total of six single-room combustion systems with a rated thermal output of between 4.5 and 10.5 kW from various regions of Germany were tested. Table 10 provides a detailed overview of the single-room combustion systems tested, including information on the type of system, the wood used, the location, the filtration technology, and the applicable emission limit values in accordance with the 1st Federal Immission Control Ordinance (1.BImSchV).

Table 10: Details of the single-room combustion systems tested with a rated output of 4.5 to 10.5 kW.

Plant ID	Type of system	Wood type	System location	NWL (kW)	Type of filter	Date of installation/ type approval	Limit values according to 1st BImSchV
P01	Wood-burning stove	Softwood (spruce)	Saxony	10.5	-	2010	Level 1
P02	Wood-burning stove	100 % hardwood (80 % beech; 20 % oak)	North Rhine-Westphalia	4.8	-	2018	Level 2
P03	Wood-burning stove	Hardwood (predominantly); softwood (rarely)	Baden-Württemberg	4.5	EP	2015	Level 2
P04	Pellet stove	Softwood (spruce)	Saxony	7	-	2023	Level 2
P05	Tiled stove	Softwood	Saxony-Anhalt	6	-	N/A	Level 1
P06	Cooker	80 % hardwood (beech); 20 % softwood (spruce)	Bavaria	7	-	2024	Stage 2

EP – electrostatic precipitator; Stage 1: from 22 March 2010 to 31 December 2014; Stage 2: after 31 December 2014

The single-room combustion systems examined represent both older systems (e.g. systems P01 and P05), which still fall under the requirements of Stage 1, and newer models, which must meet the stricter requirements of Stage 2. Of particular note is system P03, which is the only one equipped with an electrostatic precipitator and thus potentially exhibits reduced particulate matter emissions.

Table 11 contains the measured concentrations of chlorine, PCDD/Fs, dl-PCBs, and total TEQ (PCDD/F + dl-PCB TEQ) for coarse and fly ash from the single-chamber combustion plants, in each case excluding and including the limit of quantification (LOQ).

Table 11: Concentrations of chlorine (mg/kg DM) as well as PCDD/Fs, dl-PCBs and total TEQ (PCDD/F & dl-PCB) concentrations (ng/kg DM, WHO2005TEQ), excluding and including the limit of quantification (LOQ) respectively, in bottom ash and fly ash from single-chamber combustion plants.

Plant ID	Matrix	Chlorine, total	PCDD/F TEQ		dl-PCB TEQ		Total TEQ	
			excl. LOQ	incl. LOQ	excl. LOQ	incl. LOQ	excl. LOQ	incl. LOQ
Coarse ash								
P01	RBA	250	ND	0.88	ND	0.17	N/A	1.05
P02	BA	470	N/A	0.94	0.00*	0.18	0.00*	1.12
P03	RBA	<50	0.02	0.91	ND	0.17	0.02	1.09
P04	RBA	NA	0.08	0.94	ND	0.17	0.08	1.11
P05	RBA	140	ND	0.90	N/A	0.17	ND	1.07
P06	BA	1,100	N/A	0.93	N/A	0.18	N/A	1.11
Fly ash								
P01	SA	780	50.70	50.80	2.47	2.54	53.10	53.30
P02	SA	1,600	80.20	80.40	2.29	2.36	82.50	82.80
P03	VA	NA						
P04	SA	940	211.00	212.00	4.90	4.90	215.00	217.00
P05	SVA	3,300	32.90	33.10	0.67	0.76	33.60	33.80
P06	VA	1,600	190.00	191.00	8.57	8.57	199.00	199.00

BA – combustion chamber ash; NA – not analysed; ND – not detected; LOQ – limit of quantification; RA – grate ash; RBA – grate ash + combustion chamber ash; SA – ash from chimney; SVA – ash from chimney and connecting pipe; VA – ash from connecting pipe

*0.00042 ng/kg DM

As the number of plants examined is relatively low, only limited general conclusions can be drawn from the results. Nevertheless, the results and possible conclusions are discussed below.

In the coarse ash, the concentrations of PCDD/Fs and dl-PCBs were predominantly undetectable. Taking the limits of quantification into account, the PCDD/F values range between 0.88 and 0.94 ng TEQ/kg DM (WHO_{2005}) and dl-PCB values between 0.17 and 0.18 ng TEQ/kg DM (WHO_{2005}). The total TEQ value for coarse ash calculated from this therefore ranges between 1.05 and 1.12 ng TEQ/kg DM (WHO_{2005}).

In contrast, significantly higher concentrations of PCDD/Fs and dl-PCBs were measured in the fly ash. The values are somewhat higher, particularly for plant P04. This relatively new plant (built in 2023, 7 kW rated output), which burns exclusively softwood pellets, exhibits high total TEQ values of 217 ng TEQ/kg DM (WHO_{2005}) in the fly ash. The highest values were measured in a pellet stove and a kitchen stove (P04 and P06 respectively). In general, the results show higher contamination levels in fly ash compared to bottom ash.

It is not possible to determine from the available data whether the type of wood used (hardwood vs. softwood) has an influence on the formation of PCDD/Fs and dl-PCBs. Fly ash from plants that burn softwood, such as plants P01 and P05, show comparatively low values of 53.30 and 33.80 ng TEQ/kg DM (WHO_{2005}). However, the pellet stove (plant P04), which was also fuelled by softwood, exhibits the highest dioxin contamination at 217 ng TEQ/kg DM (WHO_{2005}). The picture is also inconsistent when burning hardwood. Whilst system P02 (80 % beech, 20 % spruce) achieved relatively moderate values of 82.80 ng TEQ/kg DM (WHO_{2005}), the total TEQ value for plant P06 (80 % beech, 20 % spruce) was 199 ng TEQ/kg DM (WHO_{2005}), almost as high as that of the pellet stove (plant P04).

Another possible influencing factor is the age of the system and the exhaust gas cleaning system in place. Older single-room combustion systems such as P01 (built in 2010) showed significantly lower total TEQ values at 53.30 ng TEQ/kg DM (PCDD/Fs & dl-PCBs, WHO_{2005}) significantly lower total TEQ values than newer systems such as P04 or P06. It is therefore not the case that modern appliances necessarily result in lower ash contamination.

The filter technology used and the quality of combustion also presumably play a decisive role. Electrostatic precipitators specifically reduce dust emissions. They electrically charge the dust particles and direct them towards special collection surfaces, such as internal components or the inner wall of the chimney (Lenz & Ulbricht, 2015). Consequently, the filtration technology could lead to higher levels of PCDD/Fs and dl-PCBs in the ash, as more and finer particles are captured and end up in the fly ash. An electrostatic precipitator was explicitly mentioned only for plant P03. However, due to an insufficient quantity of fly ash, no analysis could be carried out.

Overall, a clear trend emerges: fly ash contains significantly higher concentrations of PCDD/Fs and dl-PCBs than bottom ash. The concentrations found vary greatly between plants and cannot be clearly attributed to individual factors such as fuel type, plant age or design.

Figure 9 graphically illustrates the concentrations of PCDD/Fs and dl-PCBs in ng/kg DM (WHO_{2005}TEQ) from bottom ash and fly ash.

Figure 9: Concentrations in ng/kg DM (WHO_{2005}TEQ) of PCDD/Fs, dl-PCBs, and total TEQ (PCDD/F & dl-PCB TEQ) including BG in bottom ash and fly ash from single-chamber combustion plants.

CA – coarse ash, FA – fly ash. *FA from plant P03 not analysed.
Source: Own illustration, Ramboll

Figure 10 shows that by far the largest proportion of toxicity (expressed as total TEQ) is caused by PCDD/Fs. In almost all fly ash samples, the contribution of PCDD/Fs was over 95 % of the total TEQ, whilst dl-PCBs accounted for only a small proportion, usually just a few per cent. On average, PCDD/Fs in the fly ash samples contributed around 97 % to the total TEQ, whilst the proportion of dl-PCBs was around 3 %.

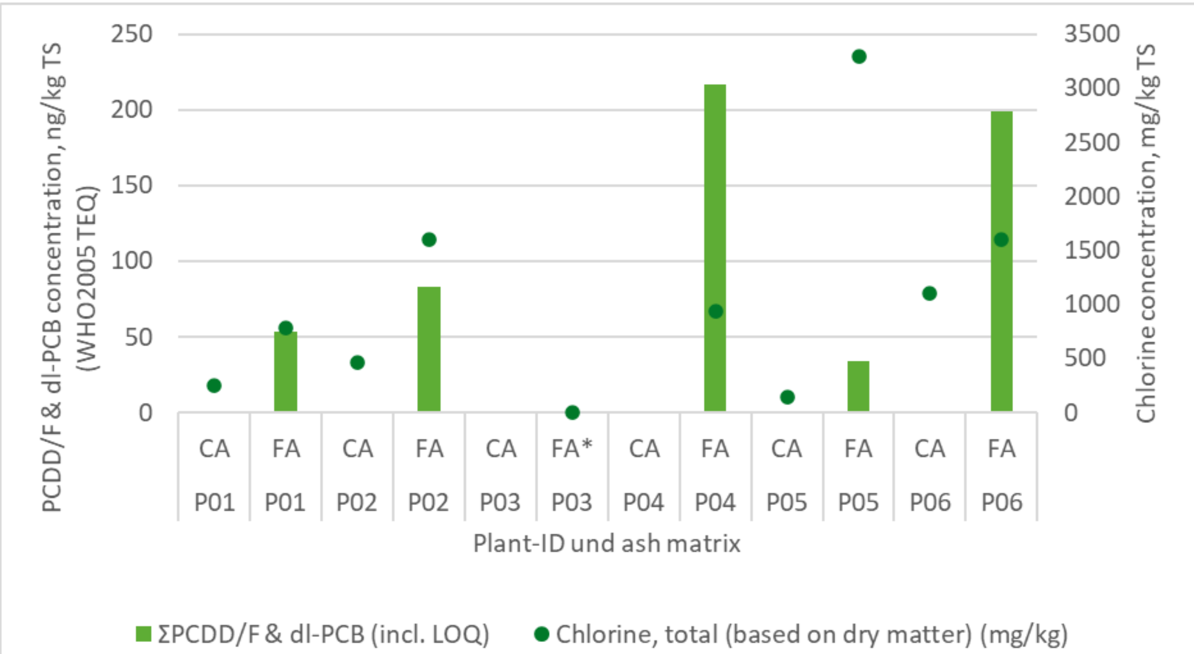
A similar picture emerges for coarse ash, where the proportion of PCDD/Fs in the total TEQ is significantly higher than that of dl-PCBs. Although the absolute concentrations in the coarse ash are very low overall, when the values including the limit of quantification are taken into account, at least ~83 % of the total TEQ comes from PCDD/Fs, whilst dl-PCBs contribute a maximum of ~17 %. On average, PCDD/Fs in the coarse ash samples contributed around 84 % to the total TEQ, whilst the proportion of dl-PCBs was 16 %.

Figure 10: Contribution of PCDD/Fs and dl-PCBs to total TEQ in ash from single-chamber combustion plants.

CA – coarse ash, FA – fly ash. *FA from plant P03 not analysed.
Source: Own illustration, Ramboll

Table 11 and Figure 11 show clear differences in the chlorine content and the associated total TEQ concentrations (PCDD/Fs & dl-PCBs) in coarse ash and fly ash from the individual room-fired boilers examined.

Figure 11: Total TEQ in ng/kg DM ($WHO_{2005}TEQ$) and chlorine content in mg/kg DM.



CA – coarse ash, FA – fly ash. *FA from plant P03 not analysed.
Source: Own illustration, Ramboll

In the bottom ash, the total TEQ values fall within a narrow range of 1.05 to 1.12 ng/kg DM, although the chlorine contents vary between 140 and 1,100 mg/kg DM (e.g. plant P05: 140 mg/kg DM; plant P06: 1,100 mg/kg DM). These low and relatively constant total TEQ values suggest that the chlorine content has no significant influence on the dioxin concentration in the coarse ash.

In fly ash, by contrast, there is a tendency for higher chlorine contents to correlate with rising total TEQ values. Plants with elevated chlorine content, e.g. Plant P02 and Plant P06, each with 1,600 mg/kg DM, also exhibited significantly higher total TEQ values of up to 199 ng/kg DM. This observation can be explained by the fact that the presence of chlorine during combustion processes promotes the formation of PCDD/Fs and dl-PCBs.

However, the relationship is not linear, which is to be expected given the small number of samples. For instance, plant P04, with an average chlorine content of 940 mg/kg DM, exhibits the highest measured total TEQ values of 217 ng/kg DM, whilst plant P05, despite a high chlorine content of 3,300 mg/kg DM, achieves only 33.80 ng/kg DM. These variations suggest that other factors also have a significant influence on the formation and distribution of PCDD/Fs and dl-PCBs.

4.1.1.2 Solid fuel boilers

A total of 14 solid fuel boilers with a rated output of 10 to 150 kW from various regions of Germany were tested. The table below Table 12 provides a detailed overview.

Table 12: Details of the solid fuel boilers tested with a rated heat output of 10 to 150 kW.

Plant ID	Type of system (boiler)	Wood type	Location of the plant	NWL (kW)	Type of filter	Date of installation/ type approval	Limit values according to 1st BImSchV
P07	Firewood	Coniferous wood (predominantly)	North Rhine-Westphalia	30	-	01/2006	since 01.01.2025 Level 1 (Section 25, 1st BImSchV)
P08	Firewood	Coniferous wood (predominantly); hardwood (rarely)	Saxony	38	N/A	10 December 2014	Level 1
P09	Firewood	Coniferous wood (predominantly); hardwood (rarely)	Bavaria	15	EP	2023	Level 2
P10	Pellet	Softwood (predominantly)	North Rhine-Westphalia	25	-	October 2013	Level 1
P11	Pellet	N/A	Saxony-Anhalt	14		1 October 2019	Level 2

Plant ID	Type of system (boiler)	Wood type	Location of the plant	NWL (kW)	Type of filter	Date of installation/ type approval	Limit values according to 1st BImSchV
P12	Pellet	50 % softwood; 50 % hardwood	Saxony-Anhalt	15	EP	01/12/2025	Level 2
P13	Pellet	N/A	Bavaria	10	EP	2024	Level 2
P14	HHS	Coniferous (predominantly) ; Deciduous (rarely)	Saxony	38	-	10 December 2009	since 1 January 2025, Stage 1 (Section 25(1) of the Federal Immission Control Ordinance)
P15	HHS	Coniferous wood (predominantly)	Saxony-Anhalt	49.5	-	1 June 2012	Level 1
P16	HHS	100 % softwood	N/A	N/A	-	N/A	Level 2
P17	HHS	N/A	Saxony-Anhalt	50	EP	1 June 2018	Level 2
P18	Woodworking industry	N/A	Bavaria	N/A	-	N/A	since 1 January 2025, Stage 1 (Section 25(1) of the Federal Immission Control Ordinance)
P19	Woodworking industry	Coated chipboard (offcuts)	North Rhine-Westphalia	100	-	08/2014	Level 1
P20	Woodworking industry	N/A	Bavaria	45–150	EP	2022	Stage 2

EP – electrostatic precipitator; HHS – wood chips; NWL – nominal heat output; Stage 0: before 2010; Stage 1: from 22 March 2010 to 31 December 2014; Stage 2: after 31 December 2014

Table 13 contains the measured concentrations of chlorine, PCDD/Fs, dl-PCBs, and total TEQ (PCDD/Fs + dl-PCBs), excluding and including BG, in bottom ash and fly ash from solid fuel boilers.

Table 13: **Concentrations of chlorine (mg/kg DM) as well as PCDD/Fs, dl-PCBs and total TEQ (PCDD/Fs & dl-PCBs) (ng/kg DM, $WHO_{2005}TEQ$), in each case excluding and including BG, in bottom ash and fly ash from solid fuel boilers with a rated output of 10 to 150 kW.**

Sample ID	Matrix	Chlorine, total	PCDD/F TEQ		dl-PCB TEQ		Total TEQ	
			excl. LOQ	incl. LOQ	excl. LOQ	incl. LOQ	excl. LOQ	incl. LOQ
Coarse ash								
P07	BA	18,000	97.80	98.00	2.18	2.18	100.00	100.00
P08	RBA	1,200	ND	0.88	N/A	0.17	N/A	1.05
P09	RBA	120	N/A	0.87	N/A	0.17	N/A	1.04
P10	RA	2,400	N/A	0.89	0.00	0.17	0.00	1.06
P11	RBA	550	0.16	1.08	ND	0.18	0.16	1.26
P12	RBA	3,000	1.05	1.33	ND	0.17	1.05	1.50
P13	RA	120	2.14	2.33	0.00	0.17	2.14	2.51
P14	RBA	620	0.17	1.00	ND	0.17	0.17	1.17
P15	RBA	290	0.01	0.92	ND	0.17	0.01	1.09
P16	RBA	280	ND	0.80	ND	0.15	N/A	0.95
P17	RBA	470	0.35	1.05	ND	0.16	0.35	1.21
P18	BA	980	0.30	1.02	N/A	0.16	0.30	1.19
P19	RA	1,700	76.50	76.70	1.090	1.16	77.50	77.80
P20	RA	310	ND	0.91	ND	0.17	N/A	1.08
Fly ash								
P07	SA	6,000	364.00	365.00	7.13	7.13	371.00	372.00
P08	SA	9,000	69.80	70.30	1.50	1.58	71.30	71.80
P09	SVA	1,600	2.12	2.30	0.00	0.17	2.12	2.47
P10	SA	6,000	208.00	208.00	21.70	21.70	229.00	230.00
P11	VA	4,100	116.00	116.00	3.41	3.48	119.00	120.00
P12	SVA	16,000	187.00	191.00	1.96	1.96	189.00	193.00
P13	VA	*Not analysed, insufficient sample material*						
P14	SA	6,700	15.40	15.50	0.33	0.40	15.80	15.80
P15	SVA	17,000	956.00	960.00	51.60	51.60	1,010.00	1,010.00
P16	SVA	1,700	1.75	1.91	ND	0.14	1.75	1.75
P17	SVA	71,000	326.00	327.00	10.10	10.10	336.00	336.00
P18	SA	5,700	566.00	571.00	16.20	16.20	582.00	587.00

Sample ID	Matrix	Chlorine, total	PCDD/F TEQ		dl-PCB TEQ		Total TEQ	
			excl. LOQ	incl. LOQ	excl. LOQ	incl. LOQ	excl. LOQ	incl. LOQ
P19	SA	86,000	1,870.00	1,870.00	38.20	38.20	1,910.00	1,910.00
P20	SVA	160,000	13,400.00	13,500.00	143.00	143.00	13,543.00	13,643.00

BA – Combustion chamber ash; LOQ – Limit of determination; RA – Grate ash; RBA – Grate ash + combustion chamber ash; SA – Ash from chimney; SVA – Ash from chimney and connecting piece; VA – Ash from connecting piece.

As with single-chamber combustion plants, the concentrations of PCDD/Fs and dl-PCBs in the coarse ash are generally lower than in the fly ash. Most values are below ~2.5 ng TEQ/kg DM. Only a few coarse ash samples contain slightly elevated concentrations of PCDD/Fs and dl-PCBs. For example, in plant P07, a log-fired boiler dating from 2006, a comparatively high total TEQ value of 100 ng TEQ/kg DM is found in the coarse ash. Another example is plant P19, a boiler in a wood-processing plant where coated chipboard scraps were incinerated. Here, a total TEQ- e concentration of 77.80 ng TEQ/kg DM was measured. The remaining plants exhibit significantly lower total TEQ values, ranging between 0.95 and 1.50 ng TEQ/kg DM.

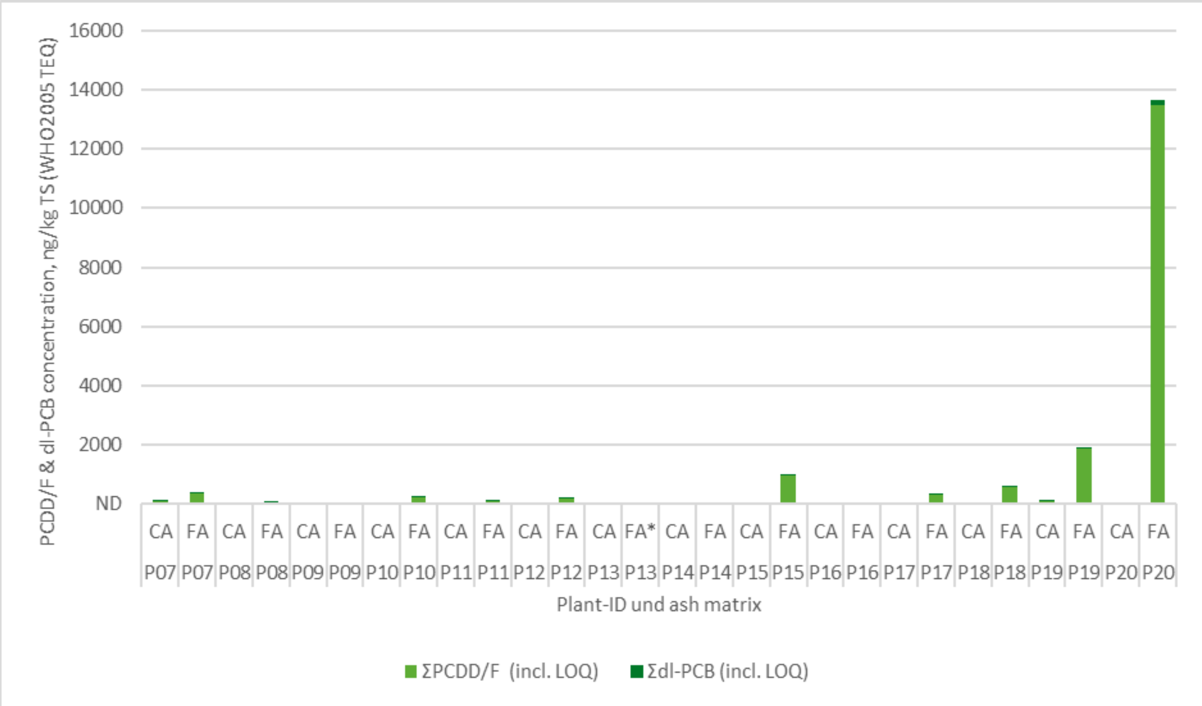
Significantly higher total TEQ concentrations were found in the fly ash. Among the smaller boilers up to 38 kW, the plants P07, P10 and P12 in particular show elevated total TEQ values in the fly ash (between 193 and 372 ng TEQ/kg DM (PCDD/Fs & dl-PCBs)). These boilers were fuelled either with logs (P07, P10) or with a mixture of softwood and hardwood pellets. In contrast, the modern plant P09, for example, which uses softwood with a low chlorine content, showed significantly lower total TEQ values (2.47 ng TEQ/kg DM (PCDD/Fs & dl-PCBs).

In the case of larger boilers with a capacity of 38 kW or more, particularly those used in the woodworking industry, dioxin concentrations were strikingly high. Particularly striking is plant P20, in which coated wood residues were incinerated. The fly ash from this plant, at 13,643 ng/kg DM (PCDD/Fs & dl-PCBs), exhibits the highest total TEQ value of all solid fuel boiler samples. At the same time, the measured chlorine content was very high at 160,000 mg/kg DM. The value for plant P19, which used coated chipboard as fuel, is also comparatively high at 1,910 ng TEQ/kg. In contrast, plant P16, for example, which burned softwood, showed a relatively low value of just 1.75 ng/kg DM (PCDD/Fs & dl-PCBs, WHO_{2005}).

Unlike in single-chamber combustion plants, where no correlation between fuel and measured dioxin concentration is apparent, a correlation is evident in solid fuel boilers. The highest total TEQ concentrations were found in the fly ash from plants in which fuels such as chipboard offcuts or wood from the wood-processing industry were burned (e.g. plant P19 and, in particular, P20). In contrast, the use of natural softwoods as fuel, particularly when used in plants such as P14 or modern plants with electrostatic precipitators such as P09 or P16, resulted in significantly lower TEQ values in the range of 1.75 to 2.47 ng/kg DM.

The following Figure 12 graphically illustrates the concentrations of PCDD/Fs and dl-PCBs in ng/kg DM (WHO_{2005}TEQ) from bottom ash and fly ash.

Figure 12: Concentrations, ng/kg DM ($WHO_{2005}TEQ$) of PCDD/Fs, dl-PCBs, and total TEQ (PCDD/F & dl-PCB TEQ) including BG in bottom ash and fly ash from solid fuel boilers



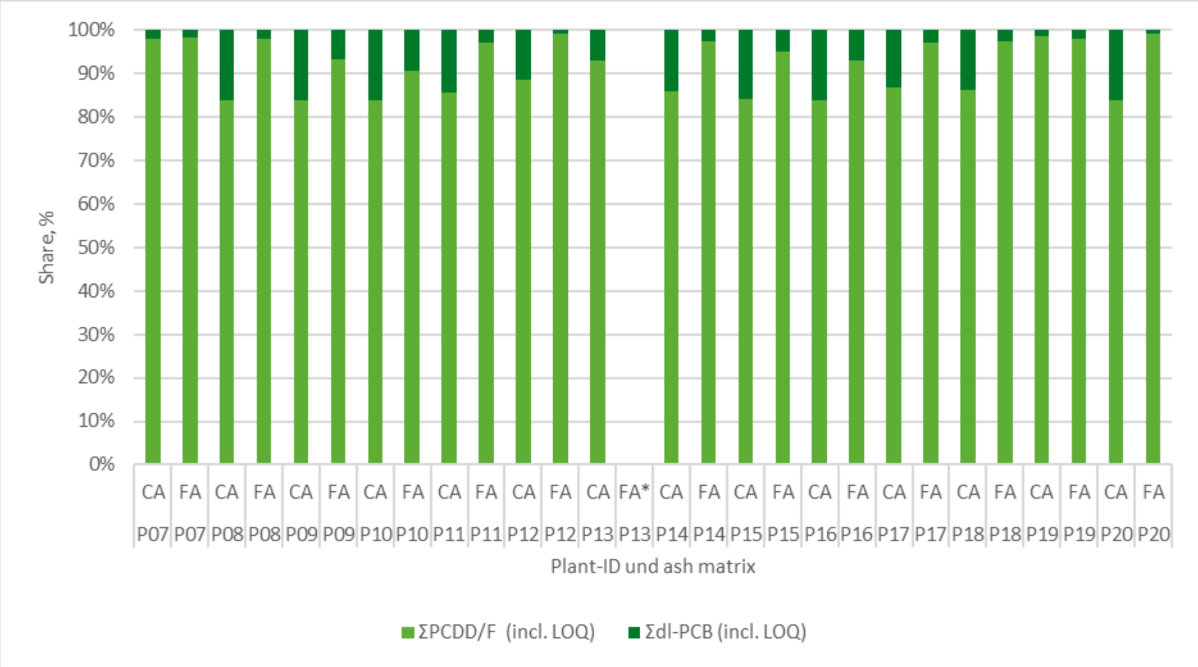
CA – bottom ash, FA – fly ash. *FA from plant P13 not analysed.

Source: Own illustration, Ramboll

The following Figure 13 shows that by far the largest proportion of toxicity (expressed as total TEQ for PCDD/Fs & dl-PCBs) is caused by PCDD/Fs. In almost all fly ash samples, the contribution of PCDD/Fs is over 90 % of the total TEQ, whilst dl-PCBs accounted for only a small proportion, usually just a few per cent. On average, PCDD/Fs in the fly ash samples contributed around 99 % to the total TEQ, whilst the proportion of dl-PCBs was around 1 %.

In coarse ash, the contribution of PCDD/Fs is consistently over 80 % of the total TEQ, whilst dl-PCBs consistently account for less than 20 %. On average, PCDD/Fs in the coarse ash samples contributed around 97 % to the total TEQ, whilst the proportion of dl-PCBs was 3 %.

Figure 13: Contribution of PCDD/Fs and dl-PCBs to total TEQ in ash from solid fuel boilers.



CA – coarse ash, FA – fly ash. *FA from plant P13 not analysed.
Source: Own illustration, Ramboll

Table 13 and Figure 14 show clear differences in the chlorine content and the associated total TEQ concentrations (PCDD/Fs & dl-PCBs) in coarse ash and fly ash from the solid fuel boilers investigated.

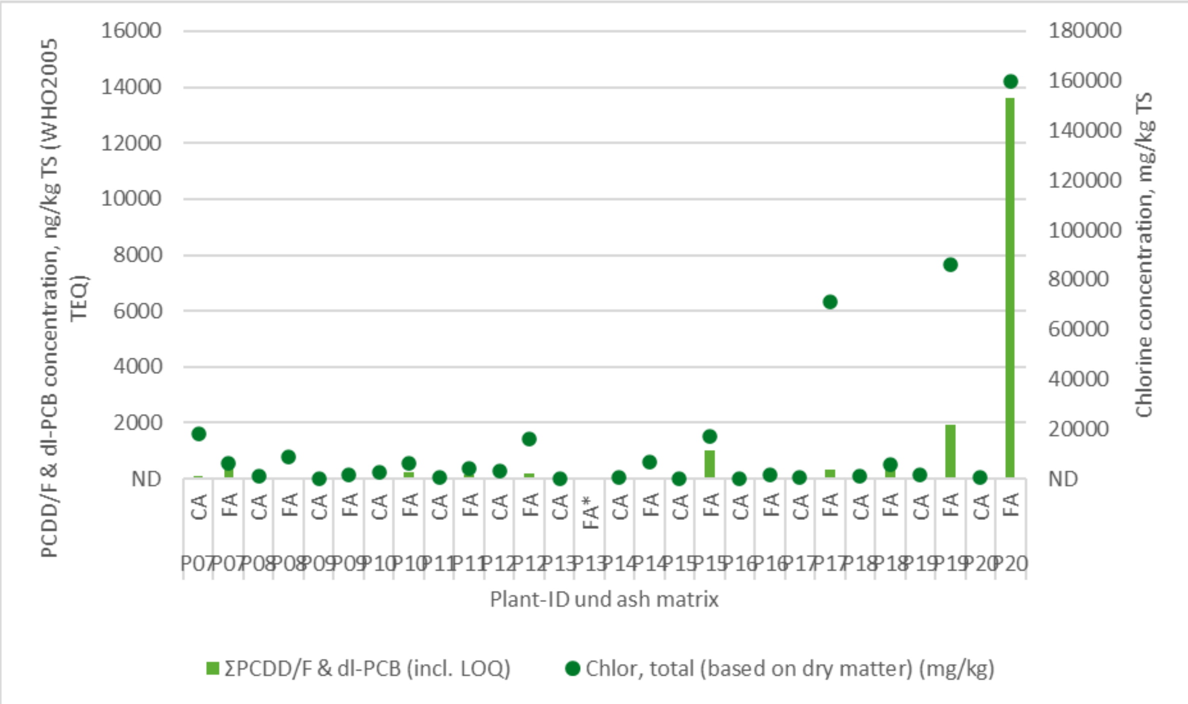
In the coarse ash, the total TEQ values range widely from 0.95 ng/kg DM (Plant P16) to 100 ng/kg DM (Plant P07). The chlorine content ranges from 120 mg Cl/kg DM (Plant P09 and Plant P13) to 18,000 mg Cl/kg DM (Plant P07). Relatively low total TEQ values in samples from sites with low chlorine content, such as site P09 with a total TEQ value of 1.04 ng/kg DM, as well as the comparatively high total TEQ values in samples from plants with higher chlorine content, such as P07 with a total TEQ value of 100 ng/kg DM, suggest that the chlorine content has a certain influence on the total TEQ in the coarse ash. However, this correlation is not consistently observed (as, for example, in plant P12 with a chlorine content of 3,000 mg Cl/kg DM and a relatively low total TEQ value of 1.50 ng/kg DM).

In fly ash, the correlation between rising chlorine concentrations and higher total TEQ values is more evident. Samples from plants with very high chlorine concentrations, such as plant P20 with 160,000 mg Cl/kg DM, also exhibit high total TEQ values, such as 13,643 ng/kg DM in this case. Samples from plants with medium chlorine content values, such as P19 with 86,000 mg Cl/kg DM and a total TEQ of 1,910 ng/kg DM, also show significantly higher total TEQ than samples from plants with low chlorine content, for example P09 with 1,600 mg Cl/kg DM and a total TEQ value of 2.47 ng/kg.

However, the relationship is not consistently observable or linear. For example, plant P12, with a chlorine content of 16,000 mg Cl/kg DM, has a total TEQ value of 193 ng/kg DM, whilst plant P18, with a chlorine content only slightly lower at 5,700 mg/kg DM, shows a significantly higher total TEQ value of 587 ng/kg DM. These deviations show that the chlorine content cannot serve as a clear indicator of the PCDD/F content in the ash.

Figure 14 shows a graphical representation of the relationship between total TEQ and chlorine content.

Figure 14: Total TEQ in ng/kg DM ($WHO_{2005}TEQ$) and chlorine content in mg/kg DM



CA – coarse ash, FA – fly ash. *FA from plant P13 not analysed.
Source: Own illustration, Ramboll

4.1.2 Medium-sized combustion plants

A total of ten fly ash samples were taken from nine different biomass combustion plants and analysed. Table 14 contains detailed information on the plants sampled, including the type of plant, the fuels used, the rated output, the type of filters, and the operating and installation data for the filters.

Table 14: Details of the medium-sized biomass combustion plants investigated

Plant ID	Type of plant	Wood type	Rated output (MW)	Type of filter	Date of commissioning /date of installation of the filter in question
P1	Thermal oil boiler	100 % HHS from landscape management	5	EP	2012/2012
P10	Hot water boiler	100 % HHS from landscape conservation	4.5	EP	2011/2011
P2	Hot water boiler + thermal oil boiler	100 % HHS	2.4 + 4.3	EP	2011/2011
P3	Hot water boiler	100 % chipboard shavings and dust	2.5	EP	2004/2023

Plant ID	Type of plant	Wood type	Rated output (MW)	Type of filter	Date of commissioning /date of installation of the filter in question
P4	Hot water boiler	98 % production residues: chipboard/defibration; 2 % production residues: solid wood/fresh wood/waste wood	8.7	FF	2010–2015
P5	Hot water boiler	30 % waste wood I; 70 % waste wood II; untreated wood	2.45	CF	2024/2025
P6*	Hot water boiler	Barley 80 % Wheat 20 %	0.275	FF	2013/2021
P7	Hot water boiler	Mixed HHS from waste wood I & II	13.8	FF	2014/2014
P8	Hot water boiler	Mixture of bark and beech sawdust	13.38	EP	2001/2001
P9	Hot water boiler	51 % waste wood I and II, 49 % natural wood	4	EP	2008/2008

EP – Electrostatic precipitator; FF – Fabric filter; HHS – Wood chips; CF – Ceramic filter.
*Cereals

Information on the measured concentrations of PCDD/Fs and dl-PCBs in fly ash from medium-sized biomass combustion plants is presented in Table 15.

Overall, the measured concentrations of PCDD/Fs and dl-PCBs in fly ash show significant variations, which depend on the type of fuel and the combustion plant.

The highest total TEQ values are found in plants P5, P7 and P9. P5 has the highest values at 5,230 ng/kg DM. This plant uses waste wood (30 % waste wood I and 70 % waste wood II) and is equipped with a ceramic filter. P9, which is operated half with waste wood, also exceeds 2,100 ng/kg DM. P7, which also uses mixed waste wood, stands at 478 ng/kg DM.

In contrast, plants that use only untreated wood or pure wood chips (e.g. P1, P2, P10) show significantly lower total TEQ values. P1 reaches around 281 ng/kg DM, P2 is around 50 ng/kg DM and P10 is only around 67 ng/kg DM.

Very low values were recorded for P8, where a mixture of bark and beech dust is burned, showing a concentration of just 1.15 ng/kg DM. This demonstrates an extremely low dioxin load despite the use of an EP and the plant's very advanced age. P6, the only plant where grain is incinerated, also shows low levels of contamination at around 24 ng/kg DM.

The type of filter and the age of the filters also play a role. For example, P5 has a ceramic filter, which is, however, associated with comparatively high total TEQ values in the fly ash. Other plants with electrostatic precipitators or fabric filters exhibit varying total TEQ concentrations in the fly ash, depending on the fuel.

The total TEQ values are particularly low at plant P8, which is operated using a mixture of bark and beech dust. Here, the total TEQ values are below 2 ng/kg DM.

This indicates that the type of fuel used has an influence on the total TEQ values in the ash from medium-sized combustion plants. For example, ash from plants in which waste wood is burned exhibits higher total TEQ values.

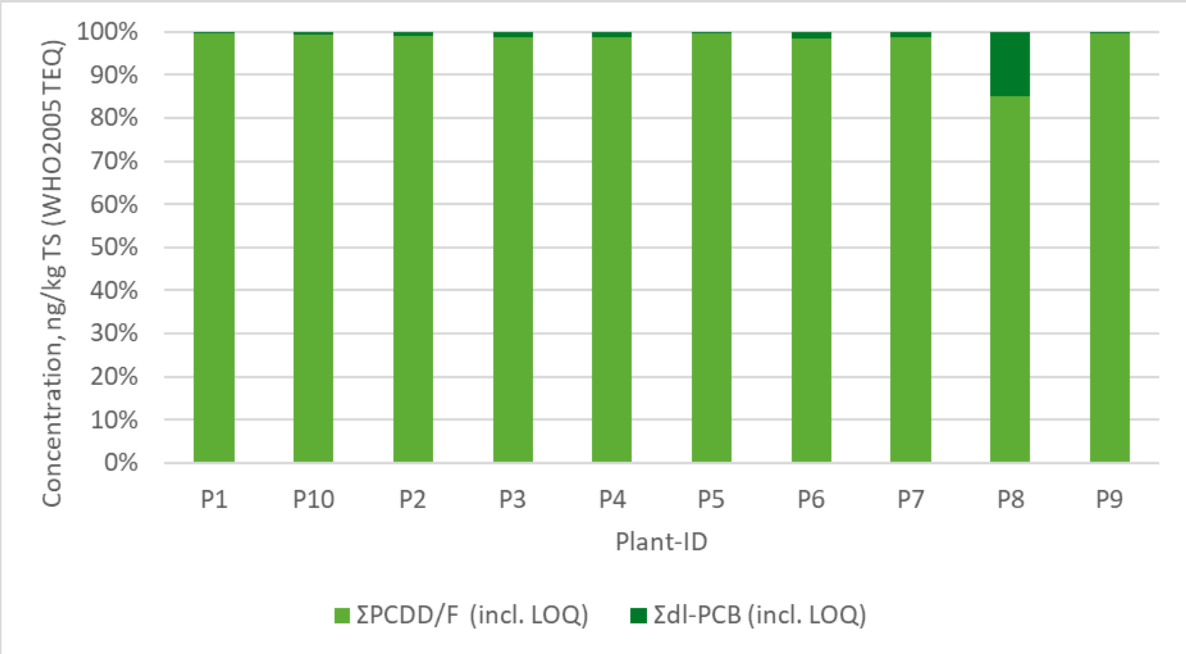
Table 15: Concentrations of chlorine (mg/kg DM) as well as PCDD/Fs, dl-PCBs, and total TEQ (PCDD/Fs & dl-PCBs) (ng/kg DM, $WHO_{2005}TEQ$) in fly ash from medium-sized biomass combustion plants.

Plant ID	Chlorine, total	PCDD/F TEQ		dl-PCB TEQ		Total TEQ	
		excl. BG	incl. BG	excl. BG	incl. BG	excl. BG	incl. BG
P1	NA	279.00	280.00	1.07	1.07	280.00	281.00
P2	NA	49.30	49.50	0.45	0.52	49.80	50.00
P3	NA	167.00	168.00	2.00	2.00	169.00	170.00
P4	NA	51.80	52.30	0.61	0.68	52.40	53.00
P5	89,000	5,170.00	5,210.00	24.50	24.50	5,200.00	5,230.00
P6	NA	23.90	24.00	0.31	0.37	24.20	24.40
P7	NA	469.00	471.00	6.72	6.72	476.00	478.00
P8	3,000	0.33	0.98	N/A	0.17	0.33	1.15
P9	NA	2,090.00	2,100.00	8.92	8.92	2,100.00	2,110.00
P10	NA	66.80	66.90	0.32	0.39	67.20	67.30

LOD – limit of detection; NA – not analysed

Figure 15 shows the contribution of PCDD/Fs and dl-PCBs to the total TEQ in fly ash from medium-sized biomass combustion plants. In all samples analysed, with the exception of P8, PCDD/Fs account for between 98 % and 99.6 % of the total TEQ. The dl-PCBs contribute only 0.4 % to 1.5 % to the total toxicity. P8 is an exception. Here, the dl-PCB proportion, at 14.8 %, is significantly higher than in the other plants.

Figure 15: Contribution of PCDD/Fs and dl-PCBs to total TEQ in ash from medium-sized biomass combustion plants.



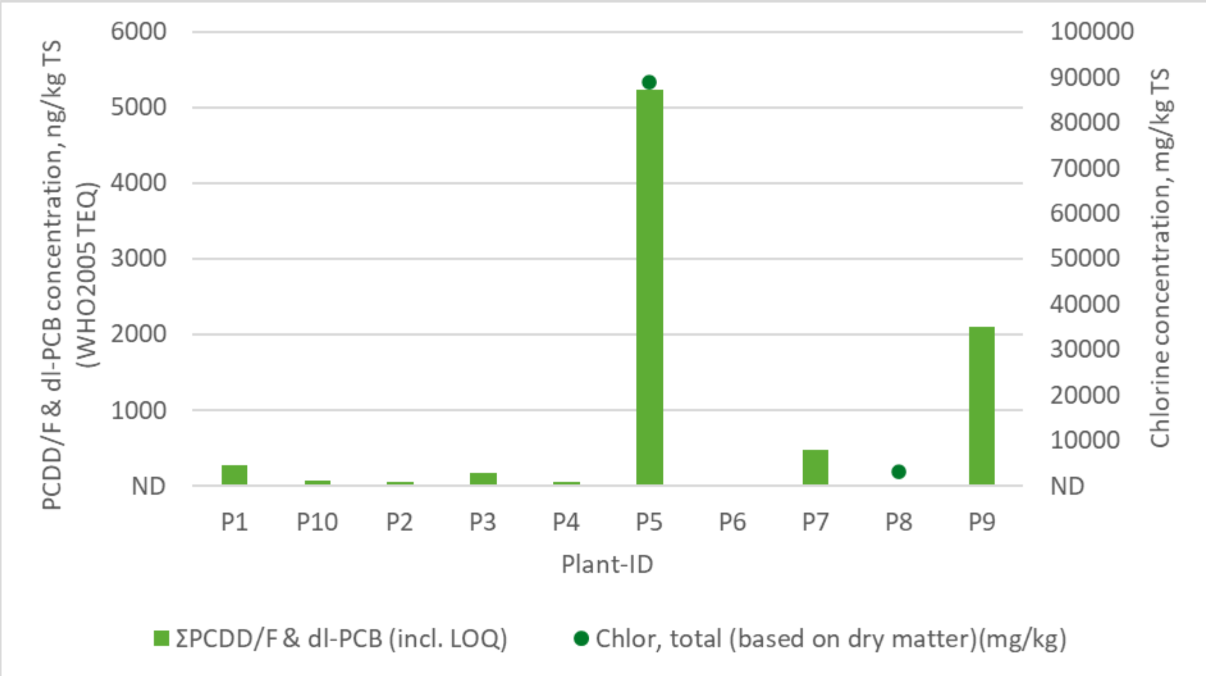
Source: Own illustration, Ramboll

Table 15 and Figure 16 show significant differences in chlorine content and the associated total TEQ concentrations (PCDD/Fs & dl-PCBs) in bottom ash and fly ash from the medium-sized biomass combustion plants investigated.

Chlorine content measurements for fly ash are available for only a few plants, which makes assessment difficult. Chlorine contents could only be determined for plants P5 and P8, at 89,000 mg Cl/kg DM for P5 and 3,000 mg Cl/kg DM for P8. Whilst P5 exhibits both a high chlorine content and elevated total TEQ values, P8 shows low total TEQ concentrations despite a comparatively moderate chlorine content.

However, as chlorine values are not available for many plants (marked as 'NA' in the Table 15), it is not possible to obtain a complete picture.

Figure 16: Correlation between total TEQ in ng/kg DM ($WHO_{2005}TEQ$) and chlorine content in mg/kg DM.



CA – coarse ash, FA – fly ash.
Source: Own illustration, Ramboll

4.2 Average PCDD/F and dl-PCB concentrations

Mean values, median values, and minimum and maximum values of the measured dioxin concentrations were determined from the analysed ash samples.

The results include measurements from small combustion plants and medium-sized biomass combustion plants, with the small combustion plants subdivided into single-room combustion systems, solid fuel boilers and boilers in wood-processing and woodworking businesses. The summary of plant types provides an overview of the range and distribution of the measured values. All concentrations are given in ng TEQ/kg $WHO_{2005}TS$.

4.2.1 Small combustion plants

4.2.1.1 Single-room combustion systems

Table 16 shows the measured PCDD/F and dl-PCB concentrations in ash samples from single-room combustion systems. As shown in the table, single-chamber combustion plants exhibit significantly lower TEQ values in bottom ash compared to fly ash. The average total TEQ value in bottom ash is 1.09 ng TEQ/kg DM ΣPCDD/F & dl-PCB. The median is almost identical to the mean, indicating a uniform distribution of TEQ values. In contrast, fly ash from single-room combustion systems has an average total TEQ value of 117.18 ng TEQ/kg DM ΣPCDD/F & dl-PCB, with a wide range from 33.80 ng TEQ/kg DM ΣPCDD/F & dl-PCB to 217 ng TEQ/kg DM ΣPCDD/F & dl-PCB. The median of 82.80 ng TEQ/kg DM ΣPCDD/F & dl-PCB is significantly lower than the average total TEQ value, indicating that few samples have high total TEQ values.

Table 16: PCDD/F and dl-PCB concentrations in the analysed ash samples from single-room combustion systems. All values are given in ng TEQ/kg WHO_{2005} DM.

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Coarse ash			
Average	0.92	0.17	1.09
Median	0.92	0.17	1.10
Min	0.88	0.17	1.05
Max	0.94	0.18	1.12
Fly ash			
Average	113.46	3.82	117.18
Median	80.40	2.54	82.80
Min	33.10	0.74	33.80
Max	212.00	8.57	217.00

Source: Own calculation

4.2.1.2 Solid fuel boilers

Table 17 shows the dioxin concentrations determined in ash samples from solid fuel boilers.

Compared to single-room combustion systems, solid fuel boilers have higher average TEQ values in both bottom ash and fly ash. Bottom ash from solid fuel boilers contains an average concentration of 10.26 ng TEQ/kg DM ΣPCDD/F & dl-PCB (almost ten times higher than in single-room combustion systems). The TEQ values are unevenly distributed, with some samples reaching a TEQ concentration of 100 ng TEQ/kg DM ΣPCDD/F & dl-PCB. Concentrations in fly ash from solid fuel boilers are also higher, with an average value of 235.42 ng TEQ/kg DM ΣPCDD/F & dl-PCB. Here too, the median is lower than the average TEQ value, indicating that only a few samples exhibit high TEQ values.

Table 17: PCDD/F and dl-PCB levels in the analysed ash samples from solid fuel boilers. All values are given in ng TEQ/kg WHO_{2005} DM.

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Coarse ash			
Average	9.92	0.35	10.26
Median	1.00	0.17	1.17
Min	0.80	0.15	0.95
Max	98.00	2.18	100.00
Fly ash			
Average	225.70	9.83	235.42
Median	135.50	2.72	156.50
Min	1.91	0.14	2.05

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Max	960.00	51.60	1,010.00

Source: Own calculation

4.2.1.3 Boilers in wood-processing and manufacturing plants

Table 18 shows the dioxin concentrations determined in ash samples from boilers at wood-processing and wood-based industries.

Compared to domestic heating systems and solid fuel boilers, the ash from the boilers of wood-processing and wood-based industries exhibits significantly higher TEQ values. Coarse ash from these plants contains an average concentration of 26.69 ng TEQ/kg DM ΣPCDD/F & dl-PCB, whilst fly ash contains an average of 5,380 ng TEQ/kg DM ΣPCDD/F & dl-PCB. The maximum value for fly ash is 13,643 ng TEQ/kg DM ΣPCDD/F & dl-PCB, almost 14 times higher than the maximum value for solid fuel boilers.

Table 18: PCDD/F and dl-PCB concentrations in the analysed ash samples from boilers at wood-processing and wood-based industries. All values are given in ng TEQ/kg DM$_{(WHO_{2005})}$.

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Coarse ash			
Mean	26.21	0.50	26.69
Median	1.02	0.17	1.19
Min	0.91	0.16	1.08
Max	76.70	1.16	77.80
Fly ash			
Average	5,313.67	65.80	5,380.00
Median	1,870.00	38.20	1,910.00
Min	571.00	16.20	587.00
Max	13,500.00	143.00	13,643.00

Source: Own calculation

4.2.2 Medium-sized combustion plants

The table below Table 19 shows the dioxin concentrations measured in ash samples from medium-sized biomass combustion plants. For each substance group, the mean, median, minimum and maximum values were calculated. All concentrations are given in ng TEQ/kg DM.

When selecting the plants, specific plants were included where higher PCDD/PCDF and dl-PCB levels in the ash were to be expected (see above). As expected, the concentration values determined from medium-sized biomass combustion plants therefore show significantly higher median and mean values overall than those from small combustion plants, with the exception of fly ash from boilers in the woodworking and processing industry. , for instance, the median value for ΣPCDD/F & dl-PCB is 118.65 ng TEQ/kg DM and the mean value is 846.49 ng TEQ/kg DM, indicating a higher overall contamination level. Compared to the low minimum values (e.g. 0.98 ng TEQ/kg for ΣPCDD/F & dl-PCB), the maximum values are very high at over 5,000 ng

TEQ/kg DM. Nevertheless, it is striking that, in contrast to small combustion plants, the median value here is significantly higher. This suggests that not only outliers, but also a large proportion of the samples are contaminated at higher levels overall.

Table 19: Dioxin concentrations in the fly ash samples analysed from medium-sized biomass combustion plants. All values are given in ng TEQ/kg DM.

Substance	Mean	Median	Minimum	Maximum value
ΣPCDD/F	842.27	117.45	0.98	5,210.00
Σdl-PCB	4.56	0.87	0.17	24.50
ΣPCDD/F & dl-PCB	846.49	118.65	1.15	5,230.00

Source: Own calculation

4.3 Pollutant loads

For the purpose of evaluating and discussing the impact of a possible change to the Annex IV limit value for PCDD/Fs and dl-PCBs in the EU POPs Regulation, the pollutant loads contained in the ash from small combustion plants and medium-sized biomass combustion plants should be determined where necessary. These can be calculated by multiplying the concentration present in the ash by the ash quantities.

As data on ash quantities are not immediately available, these are calculated using available data on energy inputs.

To calculate the pollutant loads of PCDD/Fs, dl-PCBs and the sum of PCDD/Fs and dl-PCBs in the ash, data were collected to determine the ash volumes from small and medium-sized biomass combustion plants. The aim was to determine the total quantities of ash produced.

As there are no official statistical surveys in Germany on the quantities of ash produced by small combustion plants and medium-sized biomass combustion plants, experts were consulted and data from the literature were analysed in order to obtain reliable figures.

The ash quantities determined were then multiplied by the average and median concentrations of ΣPCDD/F, Σdl-PCB and ΣPCDD/F & dl-PCB (in ng TEQ/kg DM) from the analysed samples. This made it possible to estimate the total amount of these substances contained in the ash.

The calculations were carried out for small combustion plants, broken down by plant type, for single-room combustion systems, solid fuel boilers and for boilers in wood-processing and wood-based industries, as well as separately for coarse ash and fly ash.

With regard to medium-sized combustion plants, it is not feasible to estimate the loads of PCDD/Fs and dl-PCBs on the basis of the available data for various reasons. In particular, the sampling was not representative but was carried out with the aim of sampling plants where a comparatively high level of pollutant load is to be expected, such as plants using Category A II waste wood, chipboard or grain as fuel. Against this background, the selected plants do not constitute a representative sample, and higher concentrations of PCDD/Fs and PCBs in the ash are to be expected at the sampled plants. Furthermore, only fly ash, but no bottom ash, was sampled from the plants in question. No reliable information is available on the proportions of ash content in medium-sized combustion plants when burning various fuels (including waste wood). Against this background, no estimate of the pollutant loads from these plants was made.

4.3.1 Ash quantities

To calculate the pollutant loads, the first step was to determine how much ash is produced in Germany from small combustion plants.

As no statistical surveys or official data are available on this subject, the quantities of ash were estimated based on the energy input from the fuels. To this end, the amount of fuel used in the plants was taken into account. Based on the typical ash contents of the fuels used, it was possible to calculate how much ash is produced during combustion.

To obtain relevant data and literature sources, several institutions and individuals were contacted, including ZIV, the Federal Quality Association for Wood Ash (Bundesgütegemeinschaft Holzasche e.V.), the Agency for Renewable Resources (FNR), and experts from the UBA.

The collected data and literature were checked for relevance, and suitable data were used for further calculations.

In consultation with the UBA, it was decided to use the typical ash yields specified in the relevant DIN standards for various types of wood fuel. Specifically, the values given in the DIN EN ISO 17225 series of standards were used for the calculation. The typical ash contents derived from this standard are shown in Table 20. The fuels that comply with quality class A1 are relevant for small combustion plants. The ash quantities were calculated on the basis of the fuel quantities and the typical ash yield.

Table 20: Typical ash contents of various types of wood

Wood type	Ash content, %	Ash designation	Source
Briquettes	≤1.0	A1.0	DIN EN ISO 17225-1
Pellets	≤1.0	A1.0	DIN EN ISO 17225-1
Wood chips and shredded wood	≤1.0	A1.0	DIN EN ISO 17225-1
Log wood and split wood	NA	NA	DIN EN ISO 17225-1
Sawdust	≤1.0	A1.0	DIN EN ISO 17225-1
Planing shavings	≤1.0	A1.0	DIN EN ISO 17225-1
Bark	≤1.0	A1.0	DIN EN ISO 17225-1
Round timber, chemically untreated wood residues	≤0.7	A0.7	DIN EN ISO 17225-2
Wood briquettes	≤1.0	A1.0	DIN EN ISO 17225-3

NA – not specified

Source: DIN EN ISO 17225-1, DIN EN ISO 17225-2, DIN EN ISO 17225-3

In order to estimate the pollutant loads separately for the various ash fractions (coarse ash and fly ash), the studies by Launhardt et al. (1998) are used. Taking modern combustion techniques into account, the percentages stated in Launhardt et al. were adjusted in consultation with the UBA to better reflect the current operating conditions of small combustion plants.

An overview of the percentage shares, which are used for the calculation of ash quantities, broken down into coarse ash and fly ash, is shown in Table 21 .

Table 21: Ratio of coarse ash to fly ash in small combustion plants

Ash	Percentage, %	
	Single-room combustion systems	Solid fuel boilers
Coarse ash	93	95
Fly ash	7	5

Source: Own calculations in consultation with the UBA

4.3.1.1 Small combustion plants

First, the ash quantities from small combustion plants in Germany are examined. This includes single-room combustion systems (ERF), solid fuel boilers in private households (wood-fired central heating systems, HZH) and boilers in wood-processing and woodworking businesses. The calculated ash volumes are presented in the following chapters.

4.3.1.1.1 Single-room combustion systems

According to a study by Jochem et al. (2023), total household consumption of wood fuels in 2020 amounted to 26.95 million m^3. Of this, 18.10 million m^3 was accountedfor by single-room heating systems (Jochem et al., 2023).

To express the amount in tonnes, the conversion factors (m^3/tonne) specified in the study were used for each type of firewood (see Table 22). A suitable conversion factor was available for all types of firewood except for ‘other firewood assortments’. In this case, the average of the available values was used.

Table 22: Wood consumption in single-room combustion systems in 2020

Type of wood fuel	Wood consumption, in million m^3	CF, in m^3/tonne	Wood consumption, in million tonnes
Log wood/forest log wood with bark	9.99	1.869	5.35
Firewood/forest firewood without bark	2.05	1.869	1.10
Firewood/forest firewood from gardens	1.48	1.869	0.79
Firewood/landscape management wood	0.47	1.070	0.44
Waste wood	1.37	1.730	0.79
Sawn timber offcuts	0.65	1.310	0.50
Wood chips	0.15	1.923	0.08
Wood pellets	0.80	1.875	0.43
Wood briquettes	0.63	2.107	0.30
Kindling	0.30	2.107	0.14
Other firewood assortments	0.21	1.773*	0.12

Type of wood fuel	Wood consumption, in million m^3	CF, in m^3/tonne	Wood consumption, in million tonnes
Total	**18.10**	**-**	**10.03**

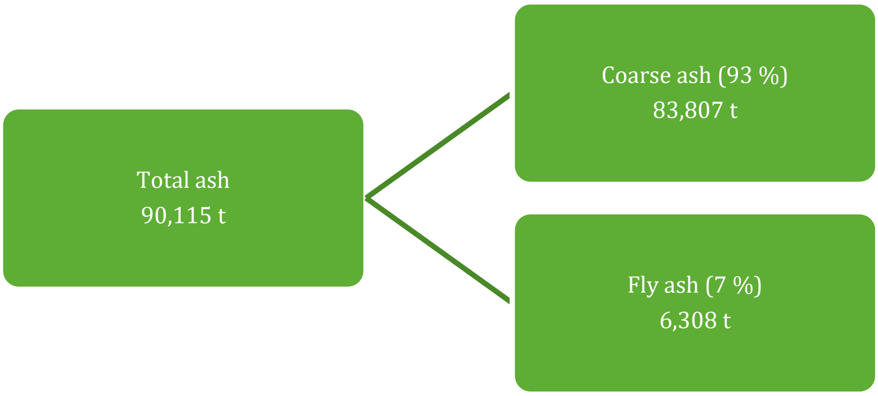
CF – conversion factor

*As no conversion factors were available for other types of firewood, the average of the available values was used.

Source: Own calculation based on Jochem et al. (2023).

The amount of ash for 2020 was estimated based on the wood consumption converted into tonnes. To calculate the ash quantities, the ash content specified in the relevant DIN standards (see Table 20) was used for the corresponding fuel types. For each firewood assortment, the appropriate ash content was applied according to fuel type (e.g. bark, untreated wood, pellets, briquettes, wood chips, etc.). This allowed the ash content to be determined more realistically and in accordance with DIN standards, resulting in an estimated ash quantity of 90,115 tonnes from domestic heating systems. This corresponds to an ash yield of 0.9 %. To further differentiate between coarse ash and fly ash, the classification in Table 21 was used. The resulting ash quantities from single-room combustion systems for the year 2020 are shown in Figure 17.

Figure 17: Ash quantities from single-room combustion systems in Germany in 2020



Source: Own calculation based on Launhardt et al. (1998) and Jochem et al. (2023) and in consultation with the Federal Environment Agency

4.3.1.1.2 Solid fuel boilers

Data from the study by Jochem et al. (2023) was also used to calculate ash quantities for solid fuel boilers. According to this study, 8.85 million $m^3$of wood fuel assortments were consumed in wood-fired central heating systems in 2020 (Jochem et al., 2023).

To express the quantities in tonnes, the conversion factors (m^3/tonne) specified in the study were used for each type of firewood (see Table 23). The appropriate conversion factor was available for all types of firewood except for 'other firewood types'. In this case, the average of the available values was used.

Table 23: Wood consumption in solid fuel boilers in 2020

Type of wood fuel	Wood consumption, in million m³	CF, in m³/tonne	Wood consumption, in million tonnes
Log wood/forest log wood with bark	3.73	1.869	2.00
Firewood/forest firewood without bark	0.50	1.869	0.27
Firewood/forest firewood from gardens	0.69	1.869	0.37
Firewood/landscape management wood	0.16	1.070	0.15
Waste wood	0.26	1.730	0.15
Sawn timber offcuts	0.17	1.310	0.13
Wood chips	0.13	1.923	0.07
Wood pellets	2.99	1.875	1.59
Wood briquettes	0.06	2.107	0.03
Kindling	0.04	2.107	0.02
Other firewood assortments	0.12	1.773*	0.07
Total	**8.85**	**-**	**4.84**

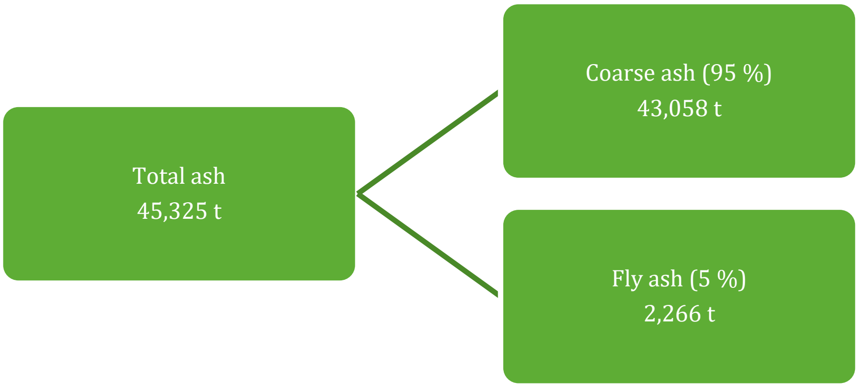
CF – conversion factor

*As no conversion factors were available for other types of firewood, the average of the available values was used.

Source: Own calculation based on Jochem et al. (2023).

The amount of ash for 2020 was estimated based on the wood consumption converted into tonnes. To calculate the ash quantities, the ash content specified in the relevant DIN standards (see Table 20) for the respective fuel types was used. For each firewood assortment, the appropriate ash content was applied according to fuel type (e.g. bark, untreated wood, pellets, briquettes, wood chips, etc.). This allowed the ash content to be determined more realistically and in accordance with the standards, resulting in an estimated ash quantity of 45,325 tonnes from solid fuel boilers. This corresponds to an ash yield of 0.9 %. To further differentiate between coarse ash and fly ash, the classification in Table 21 was used. The resulting ash quantities from solid fuel boilers for the year 2020 are shown in Figure 18 .

Figure 18: Ash quantities from solid fuel boilers in Germany in 2020



Source: Own calculation based on Launhardt et al. (1998) and Jochem et al. (2023) and in consultation with the Federal Environment Agency

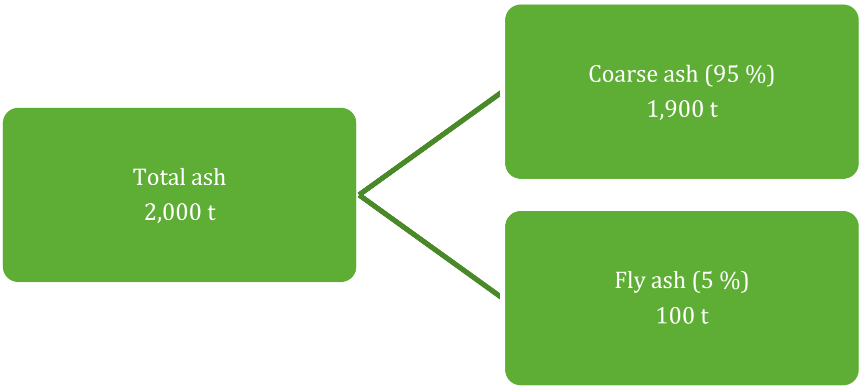
4.3.1.1.3 Boilers in wood-processing and woodworking businesses

To determine the quantities of fuels 6 and 7 used in wood-processing and woodworking businesses, a residual calculation approach was applied in consultation with the UBA, according to which approximately 100,000 tonnes of fuels 6 and 7 were consumed in 2020. However, it is important to note that these figures are subject to a high degree of uncertainty.

According to the 1st Federal Immission Control Ordinance (BImSchV), fuels 6 and 7 comprise painted, varnished or coated wood, as well as glued wood-based materials such as plywood, chipboard and fibreboard. Due to the binders, coatings and other additives they contain, the combustion of these fuels is expected to produce a slightly higher ash yield than that of untreated wood. The calculation is therefore based on an ash content of 2 %[18], rather than the approach mentioned above, which is used for single-room combustion systems and other solid fuel boilers using untreated wood.

On this basis, the corresponding ash quantities for the year 2020 were estimated. The resulting ash quantities from boilers in wood-processing and manufacturing plants for the year 2020 are shown in Figure 19.

Figure 19: Ash quantities from boilers at wood-processing and woodworking businesses in Germany in 2020



Source: Own calculations based on Launhardt et al. (1998) and Jochem et al. (2023), and in consultation with the Federal Environment Agency

[18] In consultation with the UBA

4.3.2 Resulting pollutant loads

4.3.2.1 Small combustion plants

The resulting pollutant loads in the ash from small combustion plants were calculated based on the previously calculated ash quantities (see Chapter 4.3.1) and the mean and median values of the measured TEQ concentrations of PCDD/Fs and dl-PCBs in coarse ash and fly ash.

4.3.2.1.1 Single-room combustion systems

Table 24 shows the PCDD/F and dl-PCB loads, as well as their total, in the ash from single-room combustion systems for the year 2020. All values are given in g TEQ (WHO_{2005}).

Looking at the median and mean values, it can be seen that the bottom ash (approx. 84 kt) contains an annual load of less than 0.1 g, and the fly ash (approx. 6 kt) less than 1 g of total TEQ (WHO_{2005}) for PCDD/Fs and dl-PCBs. The predominant proportion of the TEQ load stems from PCDD/F contamination in both the coarse ash (over 83 %) and the fly ash (over 96 %).

Table 24: PCDD/F and dl-PCB load in ash from single-room combustion systems in 2020. All values in g TEQ WHO_{2005}

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Coarse ash			
Average	0.077	0.015	0.091
Median	0.077	0.014	0.092
Min	0.074	0.014	0.088
Max	0.079	0.015	0.094
Fly ash			
Average	0.716	0.024	0.739
Median	0.507	0.016	0.522
Min	0.209	0.005	0.213
Max	1.337	0.054	1.369

Source: Own calculation

4.3.2.1.2 Solid fuel boilers

Table 25 shows the PCDD/F and dl-PCB loads, as well as their total, in the ash from solid fuel boilers for the year 2020. All values are given in g TEQ (WHO_{2005}).

Looking at the median and mean values, it can be seen that the bottom ash (approx. 43 kt) and fly ash (approx. 2 kt) contain an annual load of less than 0.5 g and less than 1 g total TEQ (WHO_{2005}) for PCDD/Fs and dl-PCBs respectively. The predominant proportion of the TEQ load stems from PCDD/F contamination in both bottom ash (over 86 %) and fly ash (over 95 %).

Table 25: PCDD/F and dl-PCB load in ash from solid fuel boilers in 2020. All values in g TEQ WHO_{2005}

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Coarse ash			
Average	0.427	0.015	0.442
Median	0.043	0.007	0.050
Min	0.034	0.007	0.041
Max	4.220	0.094	4.306
Fly ash			
Average	0.511	0.022	0.534
Median	0.348	0.006	0.355
min	0.004	0.0003	0.005
Max	2.176	0.117	3.289

Source: Own calculations

4.3.2.1.3 Boilers in woodworking and wood processing businesses

According to the 1st Federal Immission Control Ordinance (BImSchV), fuels listed in Section 3(1)(6) or (7) may only be used in woodworking or wood processing plants (see Chapter 2.3.1.3).

Table 26 shows the PCDD/F and dl-PCB loads, as well as their total, in the ash from boilers at woodworking and wood processing plants for the year 2020. All values are given in g TEQ (WHO_{2005}).

Looking at the median and mean values, it can be seen that the bottom ash (approx. 1.9 kt) and fly ash (approx. 0.1 kt) contain an annual load of less than 0.1 g and less than 1 g total TEQ (WHO_{2005}) for PCDD/Fs and dl-PCBs, respectively. The predominant proportion of the TEQ load in both coarse ash and fly ash stems from PCDD/F contamination (over 98 % in each case).

Table 26: PCDD/F and dl-PCB load in ash from wood-processing and woodworking plants in 2020. All values in g TEQ WHO_{2005}

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Coarse ash			
Mean	0.050	0.001	0.051
Median	0.002	0.0003	0.002
Min	0.002	0.0003	0.002
Max	0.146	0.002	0.148
Fly ash			
Mean	0.531	0.007	0.538
Median	0.187	0.004	0.191

	ΣPCDD/F	Σdl-PCB	ΣPCDD/F & dl-PCB
Min	0.057	0.002	0.059
Max	1.350	0.014	1,364

Source: Own calculations

4.3.2.2 Conclusion

In total, the annual total TEQ loads for PCDD/Fs and dl-PCBs in ash from the small combustion plants under consideration are in the low single-digit gram range. According to the estimates given above, the loads in the coarse ash (ash quantity ~129 kt) total approx. 0.6 g and in the fine ash (ash quantity ~8.7 kt) approx. 1.8 g (based on mean values in each case). It can also be concluded from this that approximately ¼ of the total TEQ load is contained in the coarse ash and ¾ in the fly ash.

5 Discussion

5.1 Comparison with values from Germany

In this chapter, the measured PCDD/F and dl-PCB concentrations in bottom ash and fly ash from small combustion plants and medium-sized biomass combustion plants are compared with values from the specialist literature in Germany. The aim is to determine whether the results of the investigations carried out as part of this project correspond with or deviate from those of other studies. It should be noted that older studies mostly used the unit ng I-TEQ/kg DM, whereas the current study used ng WHO-TEQ/kg DM (WHO $_{2005}$). The values are therefore not directly comparable, but provide a good guide (see chapter 2.3).

The results of the comparison are discussed in the following sub-chapters.

5.1.1 Small combustion plants

5.1.1.1 Single-room combustion systems

In coarse ash, the PCDD/F concentrations measured as part of this project range between 0.88 and 0.94 ng/kg DM (WHO$_{2005}$TEQ) (see Table 11). These values are close to those reported in the literature from the 1990s. According to Launhard et al., the PCDD/F values for similar plants range between 0.6 and 1.2 ng I-TEQ/kg (Launhard et al., 1998). In contrast to previous studies, dl-PCB concentrations were also measured as part of this project. However, these cannot be compared with earlier values, as no corresponding data are available. It is nevertheless likely that, both then and now, dl-PCBs contribute only a comparatively small proportion to the total TEQ value.

In fly ash, the PCDD/F values measured in this project are generally lower than those reported in the literature. They can reach up to several 1,000 ng I-TEQ/kg. In some studies, high values of over 10,000 ng I-TEQ/kg were measured (see chapter 2.3.1.1). For example, Thoma reported PCDD/F values of up to 48,240 ng I-TEQ/kg DM in ash samples from the chimney (referred to as chimney soot in the study) (Thoma, 1998), whereas in this project the maximum PCDD/F value was 212 ng/kg DM (WHO$_{2005}$TEQ). The values reported in the past are often many times higher than the current levels.

5.1.1.2 Solid fuel boilers

According to the literature, PCDD/F levels in coarse ash are generally relatively low (<100 ng I-TEQ/kg). Thus, PCDD/F TEQ values in coarse ash from untreated wood are usually low, up to around 68 ng I-TEQ/kg DM (Pieper, 2001), with outliers of up to 310 ng I-TEQ/kg DM (Launhardt et al., 1998). However, most PCDD/F values are below 10 ng I-TEQ/kg DM. Significantly higher values were measured in treated wood or wood mixtures, e.g. from 175 to 187 ng I-TEQ/kg DM (Pieper, 2001) (see chapter 2.3.1.2).

In this study, too, the measured PCDD/F values in coarse ash were in a similarly low range, mostly between 0.80 and 2.33 ng/kg DM; only one sample showed a significantly elevated value of 76.7 ng/kg. The corresponding total TEQ values, including dl-PCBs, ranged between 0.95 and 2.51 ng/kg, with the aforementioned exception of 77.8 ng/kg DM (see Table 13).

PCDD/F levels reported in the literature for fly ash are significantly higher than in bottom ash, but generally moderate (<1,000 ng I-TEQ/kg). For untreated wood, the values ranged between <1 and 1,577 ng I-TEQ/kg DM; for treated wood or special biomass such as straw or hay, up to 5,382 ng/kg (Launhardt et al, 2000) were measured (see chapter 2.3.1.2).

The fly ash values measured in the project (including BG) ranged between 1.75 and 13,643 ng/kg (PCDD/Fs & dl-PCBs (WHO_{2005}TEQ) (see Table 13). Notable are individual samples with extremely high values (>1,000 ng/kg) – comparable to the maximum values reported in the literature.

The coarse ash values measured in this project are in the lower range or even below the literature values for the proper combustion of untreated wood. In the case of fly ash, there are both values within the range of proper combustion and individual high levels of contamination, comparable to the highest values reported in the literature.

5.1.2 Medium-sized combustion plants

In the case of medium-sized biomass combustion plants, only fly ash samples were taken and analysed as part of this project.

The measured total TEQ values (PCDD/Fs & dl-PCBs WHO_{2005}) in fly ash samples from medium-sized plants vary widely, ranging from 1.15 to 5,230 ng/kg DM (PCDD/Fs & dl-PCBs WHO_{2005} , incl. BG) (see Table 15). Higher values are found in individual samples, such as from plant P5 with over 5,000 ng/kg DM (PCDD/Fs & dl-PCBs WHO_{2005} , incl. BG) or in the sample from plant P9 with approx. 2,110 ng/kg DM (PCDD/Fs & dl-PCBs WHO_{2005}, incl. BG) or the sample from plant P7 with around 478 ng/kg DM (PCDD/Fs & dl-PCBs WHO_{2005}, incl. BG).

When selecting the plants, specific plants were included where higher PCDD/PCDF and dl-PCB levels in the ash were to be expected (see above). Without exception, the higher values are associated with the combustion of Category II waste wood. This explains why the values measured in this study are in some cases several orders of magnitude higher than those reported for wood combustion in the literature reviewed. In the literature, PCDD/F concentrations in fly ash reach a maximum of 28.4 ng I-TEQ/kg (see Table 33).

5.2 Comparison with figures from other countries

As part of this project, the measured TEQ values for PCDD/Fs, dl-PCBs and the total in bottom ash and fly ash from small and medium-sized biomass combustion plants are also compared with corresponding values from other European countries.

Some of these comparative studies were provided by the UBA at the start of the project, whilst others were identified during the literature review. A total of eight relevant studies were identified and systematically evaluated. Information on the measured concentrations, the type of ash, the plant type, the combustion conditions and other relevant parameters was documented in a corresponding Excel spreadsheet.

The results from selected countries are summarised below and placed in the context of the current measurement results from this project.

5.2.1 Small combustion plants

Table 27 provides an overview of the total TEQ values (ΣPCDD/F & dl-PCB, WHO_{2005}) in bottom ash and fly ash samples from small combustion plants in various European countries.

For bottom ash in Germany, the total TEQ values measured in this project range between 0.95 and 100 ng TEQ/kg, with the measurement results predominantly falling within the range of 1 to 2 ng TEQ/kg (see Table 11 and Table 13). None of the samples exceeded the limit value of 5 µg/kg (5,000 ng/kg). Compared with other European countries, the German values fall within the mid-to-upper range. Similar or lower levels were measured in Denmark (1.30–184 ng TEQ/kg) and Sweden (up to 4.69 ng TEQ/kg). In Estonia, all measured dioxin levels were below the limit of quantification, whilst other countries such as Finland, Poland and Austria also report comparatively lower dioxin concentrations. Overall, the results show that the levels in Germany are within the range of values reported by other countries.

In Germany, total TEQ levels in fly ash ranged from 2.05 to 13,643 ng TEQ/kg. One sample exceeded the limit of 5 µg/kg, whilst two further samples exceeded 1 µg/kg. Most of the higher levels found in fly ash from Germany are directly linked to the wood-processing industry. Even higher maximum values were measured in Finland, up to 140,000 ng TEQ/kg (in one sample) (Syke, 2025). This value also exceeds the limit of 5 µg/kg. In the Finnish study, the exceptional exceedance in this sample is explained by the incineration of construction waste (Syke, 2025).

According to Zennegg (2003) (cited in Nussbaumer, 2003), soot samples from the flues of small wood-burning installations under 70 kW clearly show that PCDD/F contamination depends heavily on the fuel used. When burning untreated wood and, for example, paper for kindling, PCDD/F concentrations are relatively low. However, as soon as treated wood, plastics, aluminium foil, cardboard or household waste are co-incinerated, the measured values rise sharply. Particularly high PCDD/F concentrations were found in samples containing large quantities of glued or coated wood as well as waste (Zennegg (2003) cited in Nussbaumer, 2003).

Countries such as Denmark and Sweden also report, in line with other studies, that fly ash sometimes contains high levels of PCDD/Fs.

Table 27: Overview of total TEQ concentrations (ΣPCDD/F & dl-PCB) in ng TEQ/kg (WHO $_{2005}$) in coarse ash and fly ash samples from small combustion plants in various European countries.

Country	Number of samples	ΣPCDD/F & dl-PCB	Number of samples exceeding the following concentration values		Source
			≥ 5 µg/kg	≥ 1 µg/kg	
Coarse ash					
Denmark	10	1.30 – 184.00[2]	0	0	Frey et al. (2023)
Germany	20	0.95 – 100.00	0	0	This study
Estonia	4	< BG	–	–	Konist et al. (2022)
Finland	2	1.50 – 2.10	0	0	Syke (2025)
Poland[1]	1	2.00	0	0	Wyrzykowska et al. (2009)
Sweden	3	0.07 – 4.69	0	0	Tysklind et al. (2024)
Switzerland[1]	*Dioxin concentrations in coarse ash not analysed.*				
Austria[1]	6	0.33 – 1.71	0	0	Thanner and Moche (2002)
Austria[1]	4	0.30 – 33.50[2.3]	0	0	Obernberger, I. (1997)
Fly ash					
Denmark	10	124.00 – 1,290.00[2]	0	2	Frey et al. (2023)
Germany	20	2.05 – 13,600.00	1	3	This study

Country	Number of samples	ΣPCDD/F & dl-PCB	Number of samples exceeding the following concentration values		Source
			≥ 5 µg/kg	≥ 1 µg/kg	
Estonia	2	194.28 – 843.45	0	0	Konist et al. (2022)
Finland	32	10.00 – 140,000.00	1	6	Syke (2025)
Poland[1]	*Dioxin concentrations in fly ash not analysed.*				
Sweden	13	0.60 – 2,242.00	0	3	Tysklind et al. (2024)
Switzerland[1]	10	360.00 – 22,000.00[3]	3	8	Zenneg (2003), cited in Nussbaumer (2003)
Austria[1]	4	263.42 – 711.61	0	0	Thanner and Moche (2002)
Austria[1]	8	2.20 – 353.00[2.3]	0	0	Obernberger (1997)

[1] not representative of the whole country; [2] only PCDD/F TEQ measured; [3] TEF values not specified

5.2.2 Medium-sized combustion plants

Table 28 provides an overview of the total TEQ values (ΣPCDD/F & dl-PCB, WHO_{2005}) in bottom ash and fly ash samples from medium-sized biomass combustion plants, which were determined in various European countries.

Only limited data is available for bottom ash. In Germany, no samples of bottom ash from medium-sized biomass combustion plants were analysed. The values measured in Denmark range from 0.76 to 4.01 ng TEQ/kg, whilst in Estonia, significantly higher values ranging from 4.54 to 126.45 ng TEQ/kg were recorded in some cases. In Finland, two samples were analysed, both of which showed very low values.

There are significant differences between countries when it comes to fly ash. In Germany, the measured values ranged from 1.15 to 5,230 ng TEQ/kg, with one sample exceeding the limit of 5 µg/kg and another exceeding 1 µg/kg (see Table 15). No exceedances of the limit value were found in the other countries. Denmark recorded concentrations between 2.24 and 437 ng TEQ/kg, Finland between 0 and 220 ng TEQ/kg and Estonia between 5.23 and 278 ng TEQ/kg (see Table 28 and Table 33).

It can be observed that, in comparison with other European countries, Germany has the highest concentrations in fly ash from medium-sized biomass combustion plants, and in one case the limit value of 5 µg/g has been exceeded. However, it cannot be concluded from this that the contamination of this ash in Germany is higher than in the other countries considered. The reason for the comparatively high concentrations in fly ash in Germany is that the survey specifically sampled plants where higher PCDD/F and dl-PCB concentrations in the fly ash were to be expected due to the fuels used. All the elevated concentration values found in Germany (478 to 5230 ng TEQ/kg) are associated with the incineration of Category II waste wood. The exceedance of the limit value at 5230 ng TEQ/kg relates to plant (P5), in which waste wood is predominantly incinerated (30 % of Category I and 70 % of Category II) (see Table 14 and Table 15).

All other concentration values for fly ash from the plants investigated in Germany – where wood chips, wood production residues, bark, wood dust or grain are incinerated – range from 1.15 to 281 ng TEQ/kg, and are thus within a similar range to those in the other countries considered.

These results regarding medium-sized combustion plants indicate that, particularly when burning waste wood, limit values are likely to be exceeded in fly ash in individual cases. Contaminants in the waste wood are a possible cause, although waste wood A II should not contain any halogenated organic compounds from coatings. Nevertheless, PVC, for example, can frequently occur as a typical contaminant in waste wood A II. It contributes to the presence of chlorine during the combustion of the waste wood. This promotes the formation of PCDD/Fs and dl-PCBs and can result in a comparatively high TEQ concentration in the ash. It is therefore important to ensure that waste wood used for combustion is as free as possible from contaminants such as PVC, as this would likely result in lower TEQ values. It would therefore be advisable for operators and authorities at plants that incinerate waste wood to monitor both the contamination levels of fly ash and the purity (in terms of contaminants such as PVC) of the fuels more closely.

Table 28: Overview of total TEQ (ΣPCDD/F & dl-PCB) in ng TEQ/kg (WHO_{2005}) in ash samples from medium-sized biomass combustion plants in various European countries.

Country	Number of samples	ΣPCDD/F & dl-PCB	Number of samples above the following concentration values		Source
			≥ 5 µg/kg	≥ 1 µg/kg	
Coarse ash					
Denmark	20	0.76 – 4.01[1]	0	0	Frey et al. (2023)
Germany	*Coarse ash not analysed.*				
Estonia	9	4.54 – 126.45	0	0	Ummik et al. (2024)
Finland	2	0.00	–	–	Syke (2025)
Fly ash					
Denmark	20	2.24 – 437.00[1]	0	0	Frey et al. (2023)
Germany	10	1.15 – 5,230.00	1	2	this study
Estonia	12	5.23 – 278.89	0	0	Ummik et al. (2024)
Finland	4	0.00 – 220.00	0	0	Syke (2025)

[1] only PCDD/F TEQ measured

5.3 Comparison with limit values

In this chapter, the total concentrations of PCDD/Fs and dl-PCBs measured as part of this project are compared with the limit value of 5 µg/kg (5,000 ng/kg).

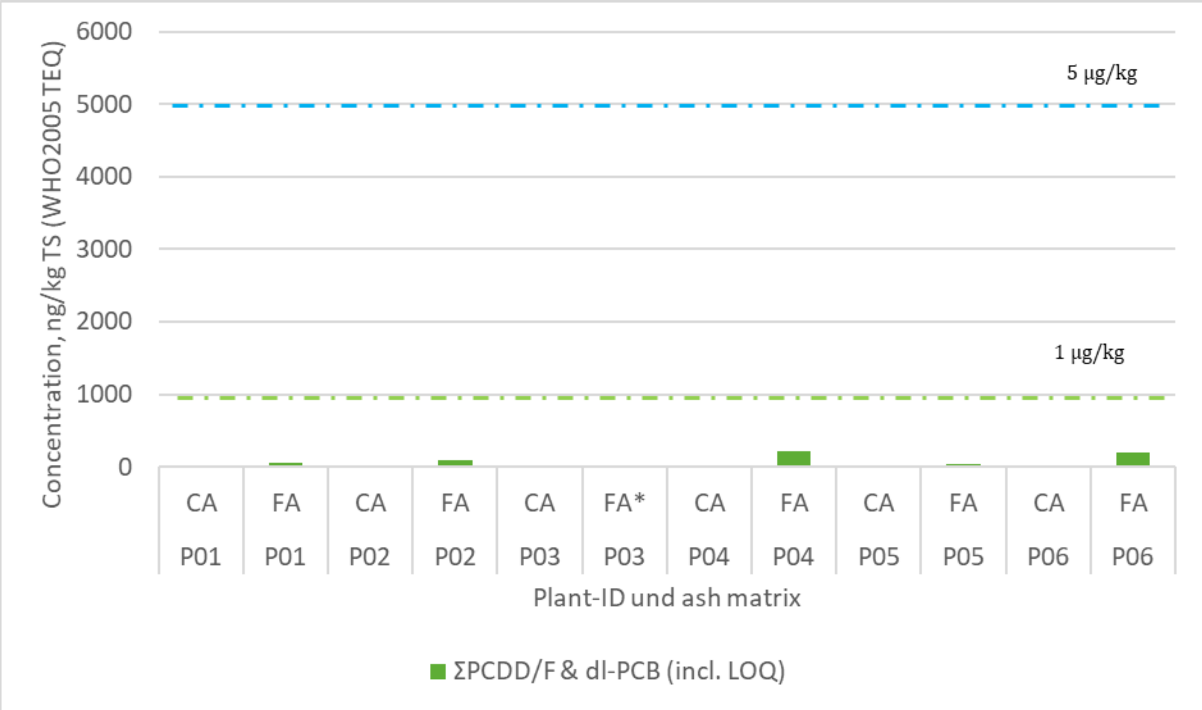
5.3.1 Small combustion plants

5.3.1.1 Single-room combustion systems

Figure 20 shows the total TEQ values (PCDD/Fs & dl-PCBs) of coarse and fly ash from single-room combustion systems compared with the limit value of 5 µg/kg and a hypothetical limit value of 1 µg/kg.

All measured total TEQ values are well below the limit value of 5 µg/kg. The highest measured total TEQ value (PCDD/Fs & dl-PCBs) is 217 ng/kg DM and amounts to only about 4 % of the limit value. Bulk ash in particular shows low concentrations. In fly ash, the values are higher, but remain well below the limit value and also below the hypothetical value of 1 µg/kg.

Figure 20: Total TEQ values (PCDD/Fs & dl-PCBs) compared with the limit value (5 µg/kg).



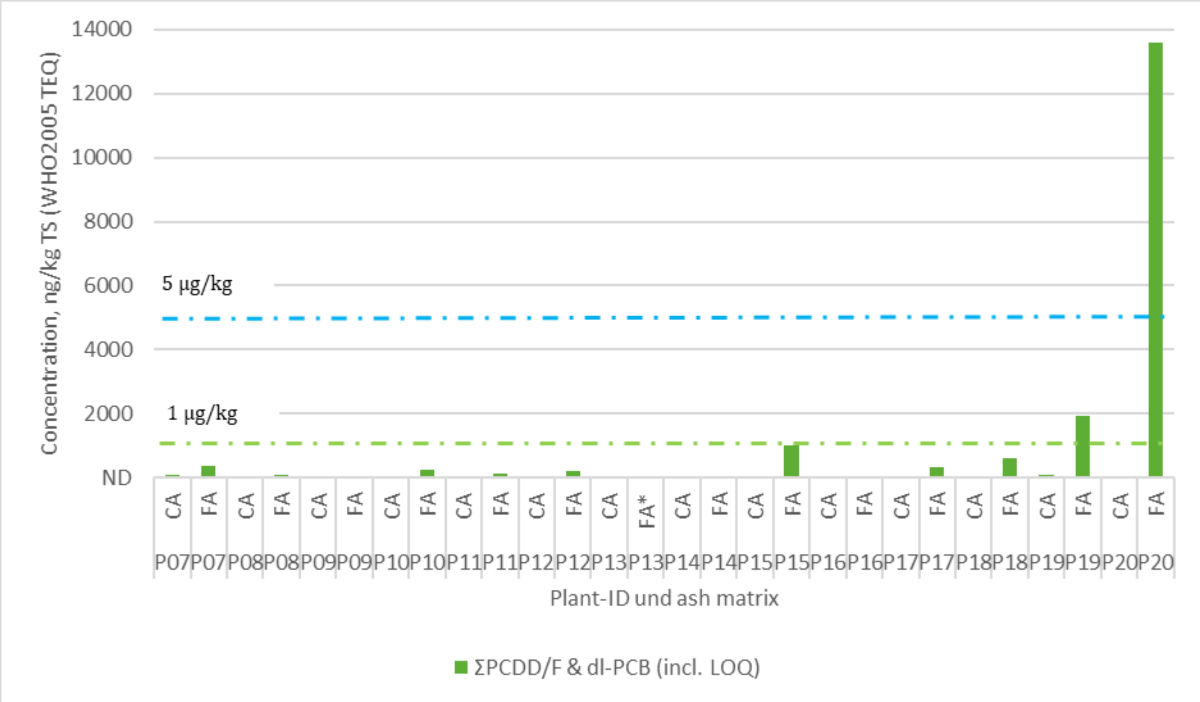
CA – coarse ash, FA – fly ash. *FA from plant P03 not analysed.
Source: Own illustration

5.3.1.2 Solid fuel boiler

Figure 21 shows the total TEQ values (PCDD/Fs & dl-PCBs) of coarse ash and fly ash from solid fuel boilers compared with the limit value of 5 µg/kg and a hypothetical limit value of 1 µg/kg.

In the samples from solid fuel boilers, one total TEQ value (fly ash from plant P20) of 13,600 ng/kg DM exceeds the limit value of 5 µg/kg. Two further total TEQ values (fly ash from plant P19 at 1,910 ng/kg DM and fly ash from plant P15 at 1,010 ng/kg DM) exceed a value of 1 µg/kg, but remain well below the limit value. All other ash samples are also well below this limit.

Figure 21: Total TEQ values (PCDD/Fs & dl-PCBs) from solid fuel boilers compared with the limit value (5 µg/kg)

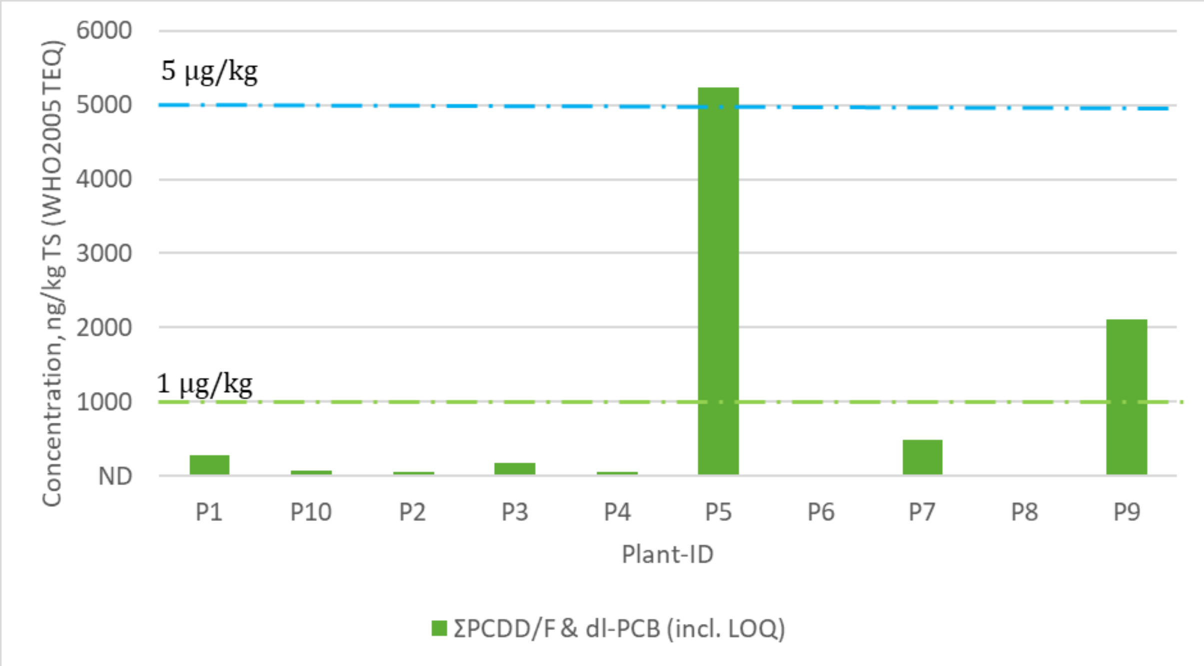


CA – heavy ash, FA – fly ash. *FA from plant P13 not analysed.
Source: Own illustration, Ramboll

5.3.2 Medium-sized combustion plants

Figure 22 shows the total TEQ values (PCDD/Fs & dl-PCBs) of fly ash collected from medium-sized biomass combustion plants compared with the limit value of 5 µg/kg as well with a hypothetical limit value of 1 µg/kg. One value is above the limit value of 5 µg/kg and one value exceeds 1 µg/kg, but remains well below the limit value. Both values are associated with the combustion of Category II waste wood. The remaining samples are well below 1 µg/kg.

Figure 22: Total TEQ values (PCDD/Fs & dl-PCBs) in ash from medium-sized biomass combustion plants compared to the limit value (5 µg/kg).



Source: Own illustration, Ramboll

5.4 Impact of the amended limit value for PCDD/Fs

Article 7 of the EU POPs Regulation governs the management of waste containing POPs. Waste containing the POPs listed in Annex IV in concentrations exceeding the specified limit values shall, in accordance with Article 7(2), be disposed of or recovered in such a way that '[...] *the POPs content is destroyed or irreversibly transformed so that the remaining waste and releases do not exhibit the characteristics of POPs*'.

The limit values set out in Annex IV are reviewed regularly and adapted to technical progress. As part of this review, on 23 November 2022 the European Parliament and the Council of the European Union adopted Regulation (EU) 2022/2400 amending Regulation (EU) No 2019/1021 on POPs.

To take account of the aggregate effect of all dl-PCBs, the dioxin-like compounds have been included in the existing group entry for PCDD/Fs in Annexes IV and V to Regulation (EU) 2019/1021. dl-PCBs are defined as substances belonging to a subgroup of 12 PCB congeners that have toxicological properties very similar to those of PCDD/Fs.

The amendment thus establishes a common threshold value for PCDD/Fs and dl-PCBs, above which waste must be managed in accordance with Article 7 of the EU POPs Regulation and the POP content must be destroyed. The new Annex IV limit, or 'lower' POP limit, is therefore 5 µg/kg (as the total concentration of PCDD/Fs and dl-PCBs in µg/kg TEQ (WHO_{2005}) instead of the previous 15 µg/kg (as a total concentration for PCDD/Fs in µg/kg TEQ (WHO_{2005}).

The text of the Regulation states: "The Commission shall review this concentration limit and, if necessary, submit a legislative proposal by 30 December 2027 at the latest to lower this limit, provided that such a reduction is feasible in the light of scientific and technical progress."

Against this background, the following is a discussion of the implications of the amended limit and whether a further reduction might be feasible.

Discussion

Based on the data researched and the PCDD/F and dl-PCB levels measured in the sampled plants, it is possible to estimate the extent of contamination in ash from small and medium-sized biomass combustion plants in Germany. On this basis, it can be discussed whether lowering the limit value is appropriate.

The discussion takes into account the method for deriving limit values in accordance with Article 7(4)(a) of the EU POPs Regulation. To narrow down the range of possible limit values, four lower (which set a lower limit on the limit value) and two upper (which set an upper limit on the limit value) limit criteria are used for the derivation of limit values (for further details, see Potrykus et al., 2015):

Lower limit criteria:

Analytical methods: Limit values should be analytically verifiable, i.e. they should be above the limit of quantification of commercially available analytical methods

Background contamination: Limit values should be set above existing background contamination levels in the environment to ensure that excavated soil with typical background contamination does not fall under the POP waste regime

Disposal and recovery capacities: Limit values should be set such that the disposal routes and capacities required for the necessary recovery and disposal are realistically available

Economic implications: Limit values should be set so that any additional disposal costs required are economically justifiable

Upper limit criteria:

Limit values: Limit values should not conflict with existing limit values

Potential environmental and health impacts: Limit values should be set at a level that avoids potential impacts on the environment and health

Re a), analytical methods:

Taking into account the limit of quantification of the laboratory where the analyses were carried out (see Table 9), it can be seen that the limits of quantification are in the lower nanogram range: For PCDD/F congeners, the limits of quantification range from 0.18 ng/kg DM (e.g. 2,3,7,8-TetraCDD) to 2.20 ng/kg DM (e.g. OctaCDD and OctaCDF). For dl-PCB congeners, the limits of quantification range from 0.78 ng/kg DM (e.g. PCB 81) to 28.00 ng/kg DM (e.g. PCB 118). For the cumulative toxic assessment according to WHO $_{2005}$TEQ, the limits of quantification are: 1.01 ng TEQ/kg DM (PCDD/Fs), 0.13 ng TEQ/kg DM (dl-PCBs) and 1.15 ng TEQ/kg DM (PCDD/Fs & dl-PCBs).

These values are well below the limit of 5 µg/kg DM and also below a hypothetical limit of 1 µg/kg DM.

The typical cost of such an analysis is around €500 (including analysis of PCDD/Fs and dl-PCBs in an ash sample). These costs can be regarded as economically justifiable.

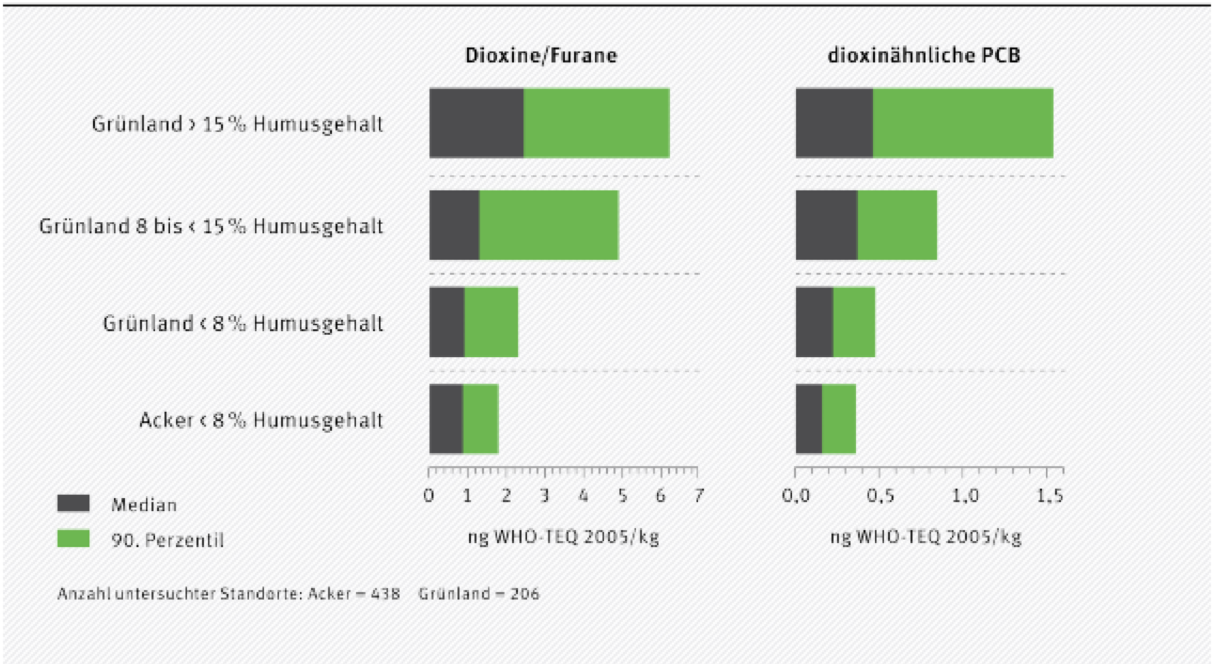
It can be concluded that suitable analytical methods are economically available.

Re b), background contamination:

Over 90 % of the PCDD/Fs and dl-PCBs released into the environment are found in soils and sediments (Behnke et al. 2018).

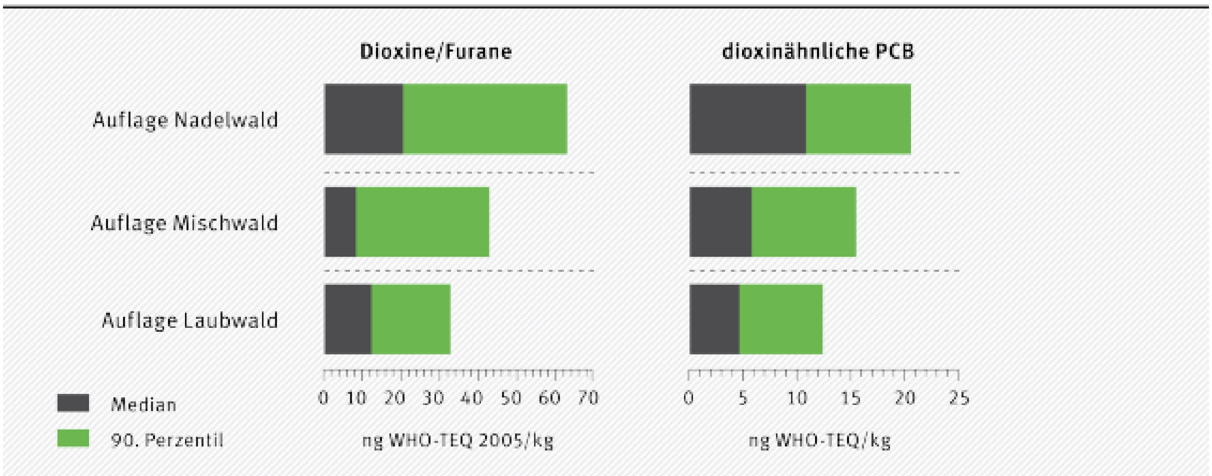
Behnke et al. summarise the median values and the upper level of nationwide background contamination (90th percentile) of PCDD/Fs and dl-PCBs in the topsoil of agricultural land (see Figure 23). The results in the figure show that in arable and grassland soils with less than 8 % humus, approximately 2 ng $WHO_{2005}TEQ$/kg of PCDD/Fs were found. As the humus content increases, particularly in grassland, the PCDD/F levels rise, reaching up to ~6 ng $WHO_{2005}TEQ$/kg in humus-rich soils. For dl-PCBs, too, levels of around 0.4 ng $WHO_{2005}TEQ$/kg were measured in low-humus arable soils. In humus-rich grassland soils, levels can rise to up to ~1.5 ng $WHO_{2005}TEQ$/kg (Behnke et al., 2018).

Figure 23: Typical concentrations of dioxins, furans and dl-PCBs in agricultural soils (greenland and field).



Source: Behnke et al. (2018)

Figure 24: Typical concentrations of PCDD/Fs and dl-PCBs in the topsoil of forest soils (coniferous forest, mixed forest, deciduous forest).



Source: Behnke et al. (2018)

Behnke et al. also report the typical values of PCDD/Fs and dl-PCBs in non-agricultural soils (see Figure 24). The results in the figure show that forest soils have significantly higher PCDD/F and dl-PCB values than agricultural soils (Behnke et al., 2018). For PCDD/Fs, the median values range between ~10 and ~20 ng $WHO_{2005}TEQ$/kg and the 90th percentile lies between ~33 and ~65 ng $WHO_{2005}TEQ$/kg.

The levels of dl-PCBs in forest soils are also higher than in agricultural soils. The median values range from ~5 to ~12 ng $WHO_{2005}TEQ$/kg, and the 90th percentile ranges from ~13 to ~22 ng $WHO_{2005}TEQ$/kg (Behnke et al., 2018).

Both the limit value of 5 µg/kg (5,000 ng/kg) and a hypothetical limit value of 1 µg/kg (1,000 ng/kg) are significantly higher than the relevant background levels in the environment in Germany. Excavated soil with typical background contamination would not be subject to the POP waste regime in either case (limit values of 5 or 1 µg/kg).

Re c) Disposal and recovery capacities:

Taking into account the results of the ash samples analysed in this study, only a few individual samples exceed a total TEQ (PCDD/Fs & dl-PCBs) that is above the limit value of 5 µg/kg or a hypothetical limit value of 1 µg/kg.

In single-chamber combustion plants (see chapter 5.3.1.1), all measured total TEQ values are well below both limits. The highest measured total TEQ value (PCDD/Fs & dl-PCBs) is 217 ng $WHO_{2005}TEQ$/kg DM; this is found in fly ash and amounts to only around 4 % of the limit value. Low concentrations are found particularly in bottom ash.

In the samples from solid fuel boilers (see chapter 5.3.1.2), only one total TEQ value (fly ash from plant P20) exceeds the limit value of 5 µg/kg, at 13,600 ng $WHO_{2005}TEQ$/kg DM. Another total TEQ value (fly ash from plant P19 at 1,910 ng $WHO_{2005}TEQ$/kg DM) significantly exceeds the 1 µg/kg limit. These elevated values are associated with the combustion of wood from the wood-processing industry. One value (fly ash from plant P15 at 1,010 ng $WHO_{2005}TEQ$/kg DM) exceeds the limit of 1 µg/kg by a minimal margin. All other total TEQ values are well below 1 µg/kg.

The only instance of the limit being exceeded occurs in the fly ash from a solid fuel boiler in which wood from the wood-processing industry is burned. The rated output is 100 kW. This scenario occurs relatively rarely and could be linked to the combustion of unusual fuels or to unusual combustion conditions. In practice, it would need to be investigated whether the limit value is exceeded more frequently in similar scenarios or whether this is an isolated case. Otherwise, the ash would have to be treated as hazardous POP waste. The quantities of fly ash produced are manageable. Approximately ½ kg of fly ash is produced per tonne of fuel. In a typical plant (solid fuel boiler, 100 kW), a quantity of approximately 12 kg of fly ash is produced per 1,000 operating hours.[19]

In the samples from medium-sized biomass combustion plants (see chapter 5.3.2), only one value exceeds the limit of 5 µg/kg (fly ash from plant P5 with 5,230 ng $WHO_{2005}TEQ$/kg DM) and one value exceeds 1 µg/kg (fly ash from plant P9 with 2,100 ng $WHO_{2005}TEQ$/kg DM), but remains well below the limit value of 5 µg/kg. In both plants, waste wood of categories I and II is incinerated.

The only instance of a limit value being exceeded occurs in fly ash from a medium-sized biomass combustion plant, which burns 30 % Category I waste wood, 70 % Category II waste wood and

[19] Own calculation based on the data presented in the report and the assumption that 25 kg of wood is incinerated per operating hour at the plant. Fly ash has a bulk density of approx. 1 $^{kg/dm^3}$. 12 kg corresponds to a volume of approx. 12 litres.

untreated wood. The rated output is 2.5 MW. The second comparatively high value (2,100 ng/kg TEQ) is also related to the combustion of waste wood. In practice, it would need to be investigated whether the exceedance of the limit value in fly ash occurs more frequently in similar scenarios (combustion of waste wood in medium-sized biomass combustion plants). If necessary, fly ash from such plants would have to be treated as POP waste if the limit value is exceeded. The quantities of fly ash produced are manageable. Approximately 1 kg of fly ash is produced per tonne of fuel[20].

Of all the samples, only two fly ashes exceed the limit value of 5 µg/kg. It should generally be borne in mind that fly ashes account for only 5 to 15 % of the total ash produced from combustion (see chapter 2.3) and that the quantity of ash potentially requiring disposal as POP waste is therefore limited. In the event of minor exceedances of the limit value, the operator also has the option of preventing such exceedances through improved fuel control.

Against this background, the project team concludes that the quantities of ash to be disposed of as POP waste are limited and that the necessary disposal and recovery capacities (e.g. underground landfill) are realistically available.

Re d) Economic impacts:

According to Bachmaier et al. (2019), the pure disposal costs for ash vary between €20 and €200 per tonne, depending on the treatment method chosen. If transport, analyses and the hire of ash containers are also taken into account, the total treatment costs range between approximately €100 and €300 per tonne (Bachmaier et al., 2019).

For POP-containing ash, the pure disposal costs are around €260/t (Link, 2014; Röhrlich, 2010).

Depending on the specific circumstances, additional costs for disposal alone may amount to between approximately €60 and €240 per tonne. Against this background, it is assumed that the quantities of ash to be disposed of as POP waste are very limited (see discussion under point c) and that any necessary disposal costs (e.g. underground landfill) are economically justifiable.

Re e) Limit values:

There are already several concentration limit values for the content of PCDD/Fs and dl-PCBs. These are shown in the Table 29.

Table 29: Current applicable limit values for PCDD/Fs and dl-PCBs in Germany.

Substance	Legislation	Regulatory object	Limit value
PCDD/F	EU Regulation (EU) No 2019/1009[21]	Fertiliser products	20 ng WHO TEQ/kg DM (0.02 µg WHO TEQ/kg DM)
PCDD/F & dl-PCB	Fertiliser Regulation (DüMV)[22]	Fertiliser products	30 ng WHO TEQ/kg DM (0.03 µg WHO TEQ/kg DM)

[20] Assuming an average total ash yield of 2 % and a fly ash content of 5 % of the total ash

[21] Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products. https://eur-lex.europa.eu/eli/reg/2019/1009/oj/eng

[22] Ordinance on the placing on the market of fertilisers, soil improvers, growing media and plant care products (Fertiliser Ordinance – DüMV). https://www.gesetze-im-internet.de/d_mv_2012/BJNR248200012.html

Substance	Legislation	Regulatory object	Limit value
PCCD/F & dl-PCB	Directive 2008/105/EC[23]	Water	6.5 ng WHO TEQ/kg DM[a] 0.0065 µg WHO TEQ/kg[a]

[a] For biota.

Where ash is used for the production of fertilisers, the relevant limit values for PCDD/Fs and PCDD/Fs & dl-PCBs shown in Table 29 must be complied with (e.g. in addition to limit values for heavy metals). The limit value of 5 µg/kg TEQ in the EU POP Regulation does not conflict with this.

Under these conditions, the existing limit values do not conflict with the existing limit value of 5 µg/kg TEQ from the EU POP Regulation or with a hypothetical limit value of 1 µg/kg TEQ.

Re f) Potential environmental and health impacts:

To mitigate risks, limit values should be set at levels that prevent potential impacts on the environment and human health and protect humans and the environment as far as possible from persistent organic pollutants.

PNEC values were sourced from the literature for the assessment. The values are presented in Table 30.

Table 30: PNEC values found in the literature.

Substance	Soil (ng TEQ_{2005}/kg)	Freshwater (ng TEQ_{2005}/L)
PCDD/F	Not identified	Not identified
dl-PCB	0.39[a] (Verbruggen and Brand, 2014)	0.385[c] (Wang et al. 2023)
	3.9[b] (Verbruggen and Brand, 2014)	

[a] Fresh weight of terrestrial vertebrates;

[b] Lipid weight of terrestrial vertebrates;

[c] Calculated on the basis of the PNEC values provided

As shown in the table, there is little information available on PNEC values for PCDD/Fs and dl-PCBs in various environmental compartments. In total, only two studies could be identified that provide data on PNEC values for dl-PCBs. No studies with corresponding values could be found for PCDD/Fs.

In the impact assessment carried out regarding waste containing PCDD/Fs, the European Commission discusses the health-related risks. As a conclusion, the Commission used a value of 0.015 mg/kg[24] TEQ as a general health-related reference value for waste (European Commission, 2021).

Both the existing limit value of 5 µg/kg TEQ in Annex IV of the EU POPs Regulation and a possible lower limit value of 1 µg/kg TEQ are lower than the health-based reference value for waste of 15 µg/kg TEQ. It can therefore be concluded that no relevant environmental or health impacts are to be expected at these limit values.

[23] Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy. https://eur-lex.europa.eu/eli/dir/2008/105/oj/eng

[24] 0.015 mg/kg = 15 µg/kg

Conclusion

In conclusion, it can be stated that, with regard to ash from small and medium-sized combustion plants, a further reduction of the limit value (e.g. to 1 µg/kg TEQ) would be possible, provided that only untreated or mechanically treated wood is burned in the plants in question.

In plants where Category A II waste wood or other types of wood that have undergone more than just mechanical processing are incinerated (such as chipboard, coated, varnished or laminated wood, which may, for example, originate from production residues from wood processing), elevated levels of PCDD/Fs and dl-PCBs may occur, and for example exceed 1 µg/kg TEQ.

In such cases, elevated values may possibly be avoided through improved fuel control. It would need to be examined whether a further reduction in the limit value can be met by implementing better fuel monitoring.

A reduction in the limit value would then need to be accompanied by awareness-raising measures and better control of potential fuel contamination to prevent limit value exceedances during the combustion of waste wood as well as wood that has not merely been mechanically treated or processed.

In addition, any assessment of whether a further reduction would be justifiable would then also need to take into account other sources of PCDD/Fs and dl-PCBs.

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A Appendix

A.1 Overview of PCDD/F content in ash and soot from single-room combustion systems in Germany, as reported in the literature.

Table 31: PCDD/F content in ash and soot from single-room combustion systems in Germany

Fuel type	Type of combustion	Combustion output, kWth	Year of installation	PCDD/F TEQ (ng I-TEQ/kg DM)	Other	Source
Coarse ash						
Untreated wood (hardwood)	Simple tiled stove, upper combustion	7	1970s–1980s	1.2	Average, samples (1), Combustion chamber (coarse fraction)	Launhardt et al. (1998)
				20	Mean, Samples (3), Combustion chamber (fine fraction)	Launhardt et al. (1998)
	Optimised tiled stove, upper combustion	8.5	Early 1990s	0.6	Average, samples (1), Combustion chamber (coarse fraction)	Launhardt et al. (1998)
				0.8	Mean, Samples (1) Combustion chamber (fine fraction)	Launhardt et al. (1998)
Wood, untreated (coniferous)	Simple tiled stove, upper combustion	7	1970s–1980s	0.7	Average, samples (1), Combustion chamber (coarse fraction)	Launhardt et al. (1998)

Fuel type	Type of combustion	Combustion output, kWth	Year of installation	PCDD/F TEQ (ng I-TEQ/kg DM)	Other	Source
				75	Mean, samples (1) Combustion chamber (fine fraction)	Launhardt et al. (1998)
	Optimised tiled stove, upper combustion	8.5	Early 1990s	0.9	Average, Samples (1), Combustion chamber (coarse fraction)	Launhardt et al. (1998)
				39	Mean, Samples (1), Combustion chamber (fine fraction)	Launhardt et al. (1998)
Fly ash (sweep ash)						
Wood, untreated (hardwood)	Simple tiled stove, top combustion	7	1970s–1980s	6.5	Average, Samples (1), Heat exchanger (fly ash)	Launhardt et al. (1998)
Wood, untreated (not defined)	Single furnace	N/A	N/A	2,015	Average, samples (33), Chimney soot	Dumler-Gradl et al. (1995)
Wood, untreated (not defined)	Tiled stove	N/A	N/A	3,453	Mean, samples (39), Chimney soot	Dumler-Gradl et al. (1995)
Wood, not defined	Wood-burning stove	N/A	N/A	45–48,240	Min-Max, Samples (9), Chimney soot	Thoma (1998)
Wood, untreated (hardwood)	Simple tiled stove, top-burning	7	1970s–1980s	7.9	Average, samples (1),	Launhardt et al. (1998)

Fuel type	Type of combustion	Combustion output, kWth	Year of installation	PCDD/F TEQ (ng I-TEQ/kg DM)	Other	Source
					Chimney soot (fine particulate matter)	

A.2 Overview of the PCDD/F and dl-PCB content in ash and soot from solid fuel boilers in Germany, as reported in the literature.

Table 32: PCDD/F and dl-PCB content in ash and soot from solid fuel boilers in Germany

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Coarse ash									
Wood, untreated	Combustion chamber, water-cooled	500 kW	Multicyclone, fabric filter	2012	N/A	N/A	4–45	Samples (2), Combustion chamber	TLLLR (2020)]
Wood, untreated (hardwood)	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	<2	<0.02	N/A	Samples (2), Rust ash	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (hardwood)	Exhaust fan and microprocessor -controlled air regulation	30 kWth	N/A	Early 90s	0.9	N/A	N/A	Average, samples (1), combustion chamber (coarse fraction)	Launhardt et al. (1998)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Wood, untreated (hardwood)	Exhaust fan and microprocessor -controlled air regulation	30 kWth	N/A	Early 1990s	4.3	N/A	N/A	Average, samples (1), combustion chamber (fine fraction)	Launhardt et al. (1998)
Wood, untreated (coniferous)	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	<2	<0.02	N/A	Samples (n/a), Rust ash	Ministry of the Environment and Transport, BW (2003)
Wood, untreated (coniferous)	Exhaust fan and microprocessor -controlled air regulation	30 kWth	N/A	Early 1990s	1.6	N/A	N/A	Mean, Samples (1), Combustion chamber (coarse fraction)	Launhardt et al. (1998)
Wood, untreated (coniferous)	Exhaust fan and microprocessor -controlled air regulation	30 kWth	N/A	Early 1990s	310	N/A	N/A	Average, samples (2), Combustion chamber (fine fraction)	Launhardt et al. (1998)
Wood, untreated (coniferous)	Combustion chamber with sliding floor, water-cooled	50 kW	N/A	≤2000	2.6–5.5	N/A	N/A	Mean, samples (6), combustion chamber	Launhardt et al. (2000)
Wood, untreated (mixed	Test facility, pre-furnace	65 kW	N/A	≤2001	68.1	N/A	N/A	Samples (1), combustion chamber	Pieper (2001)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
softwood – spruce and pine, (3:1))	system, 30 % heating load								
Wood, untreated (mixed softwood – spruce and pine, (3:1))	Test facility, pre-furnace system, 50 % heating load	65 kW	N/A	≤2001	0.012–28.4	N/A	N/A	Samples (2), combustion chamber	Pieper (2001)
Wood, untreated (mixed softwood – spruce and pine, (3:1))	Test facility, pre-furnace system, 100 % heating load	65 kW	N/A	≤2001	0.006–0.038	N/A	N/A	Samples (2), combustion chamber	Pieper (2001)
Wood, untreated (A1 waste wood)	Undershoot combustion	200 kWth	Cyclone	≤2003	<1	<0.02	N/A	Samples (n/a), Rust ash	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (bark)	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	<2	<0.02	N/A	Samples (n/a), Rust ash	Ministry of the Environment and Transport, BW (2003)
Wood, untreated (chips)	Combustion chamber, water-cooled	600 kW	Multicyclone, fabric filter	2010	N/A	N/A	3-3	Samples (3), combustion chamber	TLLLR (2020)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Wood, mixed (spruce, untreated/CKB -treated (3:1))	Test facility, pre-furnace system, 30 %–100 % load	65 kW	N/A	≤2001	51.1–162	N/A	N/A	Samples (2), combustion chamber	Pieper 2001
Wood, treated (chipboard, sulphate/chloride-cured (3:1)	Pilot plant, pre-furnace system, partial load–full load	65 kW	N/A	≤2001	175–187	N/A	N/A	Samples (2), combustion chamber	Pieper (2001)
Wood, mixed	Feed grate	550 kW	Cyclone	2012	N/A	N/A	3–18	Samples (3)	TLLLR(2020)
Grain	Feed grate, air- and water-cooled	160 kW, 2 boilers	Multicyclone, fabric filter	2014	N/A	N/A	3–46	Samples (2)	TLLLR(2020)
Cereals	Combustion chamber with moving floor, water-cooled	50 kW	N/A	≤2000	5–10	N/A	N/A	Samples (2), combustion chamber	Launhardt et al. (2000)
Straw	Feed grate, water-cooled	630 kW	Multicyclone, fabric filter	2014	N/A	N/A	<1–3	Samples (3)	TLLLR (2020)
Straw (wheat straw – chopped and palletised)	Combustion chamber with moving floor, water-cooled	50 kW	N/A	≤2000	15–33	N/A	N/A	Samples (3), combustion chamber	Launhardt et al. (2000)
Other biomass (hay – chopped and palletised,	Combustion chamber with a moving grate, water-cooled	50 kW	N/A	≤2000	10–15	N/A	N/A	Samples (3), Combustion chamber	Launhardt et al. (2000)

Fuel type	**Firing type**	**Combustion heat output**	**Filter type**	**Year of installation**	**PCDD/F (ng I-TEQ/kg DM)**	**PCB (mg/kg DM)**	**PCDD/F and PCB (ng/kg DM WHO 2005)**	**Other**	**Source**
rapeseed meal)									
Roadside vegetation	Pilot plant (0.24 MW), Grate combustion (0.5 MW), Wood chip boiler	240–500 kWth	Cyclone	≤2003	<2	<0.02	N/A	Samples (n/a), Rust ash	Ministry of the Environment and Transport, BW (2003)
Fly ash (sweep ash)									
Wood, untreated (hardwood – firewood)	Exhaust air fan and microprocessor-controlled combustion air control	30 kW	N/A	Early 90s	88	N/A	N/A	Average, samples (1), Fly ash from heat exchanger	Launhardt et al. (1998)
Wood, untreated (hardwood – log wood)	Exhaust air fan and microprocessor-controlled combustion air regulation	30 kW	N/A	Early 90s	25	N/A	N/A	Average, samples (1), Chimney soot	Launhardt et al. (1998)
Wood, untreated (hardwood – poplar wood)	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	506	<0.02	N/A	Samples (n/a), Fine ash (cyclone and ultrafine fly ash)	Ministry of the Environment and Transport, BW (2003)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Wood, untreated (hardwood)	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	896	<0.02	N/A	Samples (n/a), Fine ash (cyclone and ultrafine fly ash)	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (coniferous – firewood)	Exhaust fan and microprocessor -controlled combustion air control	30 kW	N/A	Early 90s	35	N/A	N/A	Average, 2 samples, Heat exchanger	Launhardt et al. (1998)
Wood, untreated (coniferous wood – chopped spruce)	Water-cooled combustion chamber with moving grate, 30–100 % heating load	50 kW	N/A	≤2000	23–53	N/A	N/A	Samples (2), Heat exchanger	Launhardt et al. (2000)
Wood, untreated (coniferous – chopped spruce)	Water-cooled combustion chamber with moving grate, 100 % heating load	50 kW	N/A	≤20030	61	N/A	N/A	Sample (1), Heat exchanger	Launhardt et al. (2000)
Wood, untreated (coniferous – log wood)	Exhaust fan and microprocessor -controlled combustion air regulation	30 kW	N/A	Early 1990s	84	N/A	N/A	Average, samples (2), Chimney soot	Launhardt et al. (1998)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Wood, untreated (coniferous wood – spruce and pine, (3:1))	Test facility, pre-furnace system, partial load – full load	65 kW	N/A	≤2001	97.8–117	N/A	N/A	Samples (3), Fly ash	Pieper (2001)
Wood, untreated (coniferous)	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	1,577	<0.02	N/A	Samples (n/a), Fine ash (cyclone and ultrafine fly ash)	Ministry of the Environment and Transport, BW (2003)
Wood, untreated (bark)	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	411	<0.02	N/A	Samples (n/a), Fine ash (cyclone and ultrafine fly ash)	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (chips)	Combustion chamber, water-cooled	600 kW	Multicyclone, fabric filter	2010	N/A	N/A	126	1 sample, Cyclone ash	TLLLR (2020)
Wood, untreated (municipal wood chips)	Grate firing	450 kWth	Cyclone	≤2003	<1	<0.02	N/A	Samples (2), Fine ash (cyclone and ultrafine fly ash)	Ministry for the Environment and Transport, BW (2003)
Wood, untreated	Wood-fired boiler	N/A	N/A	≤1995	1,438	N/A	N/A	Mean, samples (9), Chimney soot	Dumler-Gradl et al. (1995)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Wood, mixed (spruce, untreated/CKB -treated (3:1))	Pilot plant, pre-furnace system, partial load–full load	65 kW	N/A	≤2001	300–743	N/A	N/A	Samples (n/a), Fly ash	Pieper (2001)
Wood, mixed (HHS and wood from forest-field margin maintenance: woody green waste, 75:25 %)	Feed grate	550 kW	Cyclone	2012	N/A	N/A	5–15	Samples (2), Cyclone ash	TLLLR (2020)
Wood, treated (chipboard, sulphate/chloride-cured (3:1)	Pilot plant, pre-furnace system, partial load–full load	65 kW	N/A	≤2001	28.5–515	N/A	N/A	Samples (2), Fly ash	Pieper (2001)
Wood, unspecified	Wood-fired central heating	N/A	N/A	≤1998	6,812–41,173*	N/A	N/A	Min-Max, Samples (4), Soot, chimney	Thoma (1998)
Other biomass (LP hay, chopped)	Water-cooled combustion chamber with moving grate, 100% heating load	50 kW	N/A	≤2000	3,796	N/A	N/A	Samples (1), Heat exchanger	Launhardt et al. (2000)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Other biomass (rapeseed cake, palletised)	Water-cooled combustion chamber with moving floor, 100 % heating load	50 kW	N/A	≤2000	715	N/A	N/A	Mean, Sample (1), Heat exchanger	Launhardt et al. (2000)
Cereal (Triticale-GP, chopped)	Water-cooled combustion chamber with moving grate, 100 % heating load	50 kW	N/A	≤2000	401	N/A	N/A	Sample (1), Heat exchanger	Launhardt et al. (2000)
Cereal (Triticale-GP, chopped)	Water-cooled combustion chamber with moving grate, 100 % heating load	50 kW	N/A	≤2000	247	N/A	N/A	Sample (1), Chimney soot	Launhardt et al. (2000)
Roadside vegetation	Pilot plant, wood chip boiler	240 kWth	Cyclone	≤2003	1,114	<0.02	N/A	Samples (n/a), Fine ash (cyclone and ultrafine fly ash)	Ministry for the Environment and Transport, BW (2003)
Roadside vegetation	Grate combustion	500 MWth	Cyclone	≤2003	54	<0.02	N/A	Samples (n/a), Fine ash (cyclone and ultrafine fly ash)	Ministry of the Environment and Transport, BW (2003)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
Straw (wheat straw, chopped)	Water-cooled combustion chamber with moving grate, 100 % heating load	50 MW	N/A	≤2000	1,129	N/A	N/A	Sample (1), Heat exchanger	Launhardt et al. (2000)
Straw (wheat straw, chopped)	Water-cooled combustion chamber with moving grate, 100 % heating load	50 MW	N/A	≤2000	1,691	N/A	N/A	Sample (1), Chimney soot	Launhardt et al. (2000)
Straw (wheat straw, pelletised, 11% moisture content)	Water-cooled combustion chamber with moving grate, 100 % heating load	50 MW	N/A	≤2000	860	N/A	N/A	Sample (1), Heat exchanger	Launhardt et al. (2000)
Straw (wheat straw, pelletised, 11 % moisture content)	Water-cooled combustion chamber with moving grate, 30 % heating load	50 MW	N/A	≤2000	5,382	N/A	N/A	Sample (1), Heat exchanger	Launhardt et al. (2000)
Other biomass (LP hay, chopped)	Water-cooled combustion chamber with moving grate,	50 kW	N/A	≤2000	1,711	N/A	N/A	Sample (1), Chimney soot	Launhardt et al. (2000)

Fuel type	Firing type	Combustion heat output	Filter type	Year of installation	PCDD/F (ng I-TEQ/kg DM)	PCB (mg/kg DM)	PCDD/F and PCB (ng/kg DM WHO 2005)	Other	Source
	100 % heating load								
Fly ash (filter ash)									
Wood, untreated (chips)	Combustion chamber, water-cooled	600 kW	Multicyclone, fabric filter	2010	N/A	N/A	91	Samples (2), Filter ash	TLLLR (2020)
Cereals	Feed staircase grate (5 steps), water-cooled	950 kW	Multicyclone, Helbig fabric filter	2013	N/A	N/A	67-271	Samples (2), Filter ash	TLLLR (2020)
Other biomass (75% hay, 10 % reed, 15 % wood)	Feed staircase grate (5 steps) and combustion chamber	800 kW	Multicyclone, Helbig fabric filter	2014	N/A	N/A	168–2,100	Samples (3), Filter ash	TLLLR (2020)

*Value calculated on the basis of the concentrations of the individual PCDD/F compounds specified in the report

A.3 Overview of the PCDD/F content in ash and soot from medium-sized combustion plants in Germany, as reported in the literature.

Table 33: PCDD/F and dl-PCB content in ash and soot from medium-sized combustion plants in Germany

Fuel type	Type of combustion	Thermal output	Filter type	Year of construction	PCDD/F (ng I-TEQ/kg)	PCB (mg/kg DM)	PCDD/F and dl-PCB (ng/kg DM WHO 2005)	Other	Source
Coarse ash									

Fuel type	Type of combustion	Thermal output	Filter type	Year of construction	PCDD/F (ng I-TEQ/kg)	PCB (mg/kg DM)	PCDD/F and dl-PCB (ng/kg DM WHO 2005)	Other	Source
Wood, untreated (hardwood)	Grate combustion	1.0 MW_{th}	Cyclone	≤2003	<1	<0.02	N/A	Samples (n/a), Coarse ash	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (coniferous)	Rust combustion	2 x 1.0 MW_{th}	Cyclone	≤2003	<1	<0.02	N/A	Samples (n/a), Coarse ash	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (residual wood A1)	Grate and injection firing	11.0 MW_{th}	Cyclone + electrostatic precipitator	≤2003	<1	<0.02	N/A	Samples (n/a), Coarse ash	Ministry for the Environment and Transport, BW (2003)
Wood, treated (waste wood A2)	Grate and injection firing	20.0 MW_{th}	Electrostatic precipitator	≤2003	<1	<0.02	N/A	Samples (n/a), Coarse ash	Baden-Württemberg Ministry of the Environment and Transport (2003)
Wood, mixed (HHS)	Feed grate	19.5 MW_{th} + 5.36 MW_{el}	Cyclone, fabric filter	2006	N/A	N/A	3–4	Samples (10), Combustion chamber ash	TLLLR (2020)
Straw (bales, chaff)	5-zone vibrating	49.8 MW_{th} + 11.8 MW_{el}	Cyclone, flat-tube sorption fabric filter	2013	N/A	N/A	3–7	Samples (10), Combustion chamber ash	TLLLR (2020)

Fuel type	Type of combustion	Thermal output	Filter type	Year of construction	PCDD/F (ng I-TEQ/kg)	PCB (mg/kg DM)	PCDD/F and dl-PCB (ng/kg DM WHO 2005)	Other	Source
	grate, water-cooled								
Fly ash (sweep ash)									
Wood, untreated (hardwood)	Grate combustion	1.0 MW_{th}	Cyclone	≤2003	4.5	<0.02	N/A	Samples (n/a), Fine ash	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (coniferous)	Rust combustion	2 x 1.0 MW_{th}	Cyclone	≤2003	<1	<0.02	N/A	Samples (n/a), Fine ash	Ministry for the Environment and Transport, BW (2003)
Wood, untreated (residual wood A1)	Grate and injection firing	11.0 MW_{th}	Cyclone + electrostatic precipitator	≤2003	<1	<0.02	N/A	Samples (n/a), Fine ash	Ministry of the Environment and Transport, BW (2003)
Wood, treated (waste wood A2)	Grate and injection firing	20.0 MW_{th}	Electrostatic precipitator	≤2003	28.4	<0.02	N/A	Samples (n/a), Fine ash	Ministry of the Environment and Transport, BW (2003)
Fly ash (filter ash)									
Straw (bales, chaff)	5-zone vibrating grate, water-cooled	49.8 MW_{th} + 11.8 MW_{el}	Cyclone, flat-tube sorption fabric filter	2013	N/A	N/A	5–8	Samples (3), fabric filter ash	TLLLR (2020)

HHS – Wood chips

A.4 Overview of the PCDD/F content in ash and soot from a wood-processing plant in Germany, as reported in the literature.

Table 34: PCDD/F content in ash from the wood processing plant in Germany

Fuel type	Firing method	Combustion capacity, MW_{th}	Year of plant construction	PCDD/F TEQ (ng/kg TEQ BGA)	Other	Source
Coarse ash						
Wood	Wood processing plant	N/A	≤1994	0.31–0.66	Samples (10), Soil ash	Pohlandt et al. (1994)
Fly ash (sweep ash)						
Wood	Wood processing plant	N/A	≤1994	121–215	Samples (10), Fly ash	Pohlandt et al. (1994)

B Appendix

B.1 Procedure for representative sampling of coarse ash and fly ash from small combustion plants

1. Objective

The objective of this sampling is to obtain a representative sample of coarse ash[1] and fly ash[2] from small combustion plants. The sample is to be used for determining the chemical composition (in this case PCDDs, PCDFs, dl-PCBs and chlorine).

2. Health and safety

Appropriate occupational safety measures must be provided for when planning the sampling. These include:

- Disposable gloves (DIN EN 388),
- Dust mask (FFP II)
- Safety goggles (DIN EN 166).
- kitchen scale

3. Sampling point

Sampling should be carried out at the deposit site of the bottom ash (in the combustion plant/combustion chamber) or the fly ash (at the base of the chimney and the connection to the chimney). The deposit site should be selected so that it is representative of the entire sample.

4. Sampling device

A suitable sampling device (no PVC, no wood) must be used for sampling. The sampling device should be of sufficient size to take a sufficiently large sample. The sampling device must not be contaminated. This means it must be free from any adhering residues. The devices used for sampling must be made of materials that do not affect the sample in terms of the properties and constituents to be analysed (no PVC, no wood).

→ Preferably, equipment (e.g. a clean shovel) made of stainless steel or high-quality plastic (PP, PE) should be used.

ATTENTION: As the sample consists of ash, it must be ensured that it has **cooled** completely. This is particularly critical to check and ensure in the case of coarse ash. For a coarse ash sample, it should be ensured that the operator has not operated the furnace for more than 48 hours prior to sampling. The ash sample must not show any noticeable rise in temperature. When measuring with a thermometer, the core temperature of the sample must not exceed the ambient temperature. In unoccupied areas of the building (basement/attic), this is between 10 and 18 °C, and in occupied areas of the building between 18 and 25 °C.

5. Packaging and transport

The sample must be placed in clean, dry, moisture-proof, largely airtight and sufficiently large sealable containers and sealed. The containers must be designed in such a way that no loss of pollutants is possible during transport and storage. It is advisable to allow for a reserve of containers for sample divisions and additional samples. The following requirements also apply to the containers:

- the wall thickness of the containers must be sufficient to withstand the stresses encountered during sampling and transport
- the containers must be selected so that no sorption of pollutants occurs in or on the packaging walls and no contamination of the samples occurs due to constituents of the packaging material,
- the containers must be made of a material that is compatible with the waste and the expected range of pollutants. This is to ensure that the containers neither deform nor rupture as a result of chemical reactions,
- The sample container must be stored in a dry, dark place.

→ The plastic bags provided must be used for packaging the samples. Important! Ensure that the sample has cooled down (see point 4).

6. Sampling procedure

Sampling is carried out according to the following procedure:

1. Where possible, individual samples are taken from the entire cross-section of the material present (for both bottom ash and fly ash) using the sampling device and combined to form a composite sample. Sampling should be carried out in such a way that the sample represents the entire quantity of bottom ash or fly ash. When sampling coarse ash, ash may be taken from the grate and from the combustion chamber (please note the ratio of quantities or the approximate quantities of the individual fractions, in addition to the number of individual samples, in the sampling record). When sampling fly ash, the ash may be taken from the chimney and from the connection to the chimney.
2. The samples taken individually using the sampling device (individual samples) are placed in the designated sampling containers to form the composite sample (for coarse ash and fly ash respectively).
3. The sampling container (plastic bag) is sealed as airtight as possible using a cable tie provided, labelled with a label provided, marked as specified, and documented with photographs of the front and back.
4. The labels on the samples are marked as follows:

"P#Number#_Fireplace" or "P#Number#_Chimney and connecting piece" – where #Number# should be replaced with the corresponding number on the sheet listing the selection and allocation of small combustion plants.

The pre-printed labels provided are to be used for labelling the samples.

7. Sample quantity

- Where possible, the sample quantity should be at least 180 g. If this is not feasible, a smaller quantity is acceptable, provided it is not less than 60 g.
- To ensure this, the sample should be weighed after the composite sample has been prepared. A suitable kitchen scales are sufficient for this purpose. A bathroom scales are not accurate enough.
- Note: the density of fly ash is less than 1/10 that of water. This means that a 200 g fly ash sample corresponds to a sampling volume of approximately 2 L.

8. Sampling documentation

The sampling is documented in accordance with the attached sampling protocol.

9. Laboratory order

The samples taken are handed over to the laboratory with a laboratory order.

10. Sample transport

The sample is sent to the laboratory in a suitable, sturdy cardboard box. This packaging ensures that the sample containers, in this case plastic bags, are not damaged during transport. The box is marked or labelled with the laboratory's address and the sender's details.

11. Notes

- Sampling is carried out by trained specialist staff.
- The sampling is carefully documented.
- The sample is stored and transported appropriately.
- Sampling should take place at a location where the coarse ash/fly ash is not contaminated by other materials.
- Sampling should be carried out in such a way that the sample is not contaminated by rain, snow or other substances. If contamination is detected on site, this must be noted in the sampling report and documented photographically.

Appendix 1: Sampling report

Appendix 2: Laboratory request form

B.2 Sampling protocol within the framework of the 'UBA POPs in Waste' project

Figure 25: Sampling protocol for small combustion plant as part of the "UBA POP in Waste" project

1	**Plant**	*P___*
2	**Samples**	*P___Fireplace/chimney and connecting piece*
		P___Fireplace/chimney and connecting piece

Please enter the sample number from the small combustion plant data sheet in the fields highlighted in grey, along with the selection and classification of the small combustion plants; please cross out any information that does not apply

A. General information:

3	**Initiator / Client**	Ramboll Deutschland GmbH on behalf of the Federal Environment Agency
4	**Operator / Operation**	Private
5	**Postcode and town of the facility**	
6	**Reason for sampling**	Preliminary waste characterisation analysis
7	**Date of sampling (DD.MM.YYYY)**	
8	**Sampler / Department**	

B. Details of the combustion plant:

9	**Type of combustion plant**	☐Wood-burning stove ☐Pellet stove ☐Tiled stove ☐Log-burning boiler ☐Pellet boiler ☐Wood chip boiler ☐Boiler in the woodworking industry ☐Other:
10	**Type of emission reduction technology**	☐None ☐Electrostatic precipitator ☐Catalytic converter ☐Other:
11a.	**Date of installation/date of type approval (YYYY)**	
11b.	**Limit values according to 1. BImSchV**	☐Stage 0 (before 2010) ☐Stage 1 (from 22 March 2010 to 31 December 2014) ☐Stage 2 (after 31 December 2014)

12	**Output of the combustion plant (in kW)**	
13	**Condition of the fireplace**	☐In good condition ☐Defects Brief description of defects:

C. General information on the fuel:

14a.	**Exclusion of coal as a fuel**	☐Confirmation that no coal has been burnt in the last 6 months, only natural wood (except for wood-processing businesses → Question 15e)
14b.	**Type of wood:**	Coniferous wood: ☐exclusively ☐predominantly ☐rarely ☐not at all Hardwood: ☐exclusively ☐predominantly ☐rarely ☐not at all Further Please specify the main timber species if known (birch, beech, pine, fir, poplar, alder, maple):
15a.	**Fuel moisture**	Fuel moisture content is below 25% ☐Yes ☐No
15b.	**Fuel quality – suspected contaminants/hazards (if any, e.g. from previous sampling)**	
15c.	**For single-room combustion systems:**	Have wood briquettes been used in the last 6 months? ☐Yes ☐No If wood briquettes have been used in the last 6 months: Quantity of wood briquettes used: ☐exclusively ☐mainly ☐predominantly ☐rarely
15d.	**For wood chip firing:**	☐The wood chips used contain no impurities (needles/leaves) ☐The wood chips used contain few impurities (needles/leaves) ☐The wood chips used contain a lot of impurities (pine needles/leaves) ☐The wood chips used have a fuel moisture content of over 25% ☐Yes ☐No
15e.	**Wood processing and manufacturing businesses**	Use of treated wood (fuel numbers 6 and 7) ☐exclusively ☐mainly ☐predominantly ☐rarely
16	**Testing laboratory**	Eurofins GfA Lab Service GmbH, Am Neuländer Gewerbepark 4, 21079 Hamburg

D. Information on sampling:

Ash sample from the grate and the combustion chamber (coarse ash; fireplace)		
Sample identification (see 2):		
17	**General description of the sample** (visual abnormalities/contaminants, e.g. unburned plastic parts, nails, etc.; if present, approximate percentage content/olfactory abnormalities)	
18	**Sample quantity**	Quantity in g (approximate) for grate ash: Quantity in g (approximate) for combustion chamber ash: Total in g:
19	**Duration of storage of the sample material at the sampling point** (time in days/weeks since the last emptying/cleaning)	
20	**Factors affecting the material at the time of sampling** (if applicable (wet/dry, ...))	
21	**Sampling equipment and material**	
22	**Description of the sampling** (if possible; collection of individual sample(s) by device, description of selection/collection from the total quantity available)	
23	**Number of individual samples (IS)** (if feasible)	
24	**Sample preparation steps** (if carried out)	
25	**Observations during sampling / Comments** (if any)	
26	***Photographic documentation:*** ***Please insert photos of the samples here (one to two photos per sample)***	

Ash sample from the chimney and the connecting piece (fly ash)		
Sample identification (see 2):		
17	**General description of the sample** (visual abnormalities/contaminants, e.g. unburned plastic parts, nails, etc.; if present, approximate percentage content/olfactory abnormalities)	
18	**Sample quantity (in g)**	Amount in g (approximate) for ash from the chimney: Quantity in g (approximate) for ash from the connecting piece: Total quantity in g:
19	**Duration of storage of the sample material at the sampling point** (time in days/weeks since the last emptying/cleaning)	
20	**Factors affecting the material at the time of sampling** (if applicable (wet/dry, ...))	
21	**Sampling equipment and material**	
22	**Description of the sampling** (if possible; collection of individual sample(s) by device, description of selection/collection from the total quantity available)	
23	**Number of individual samples (IS)** (if feasible)	
24	**Sample preparation steps** (if carried out)	
25	**Observations during sampling / comments** (if any)	
26	***Photographic documentation:*** ***Please insert photos of the samples here***	

27 Test reports from the testing laboratory (to be added later by the client):

Coarse ash:

Fly ash:

Source: Own illustration, Ramboll

C Appendix

C.1 Plant profile for medium-sized combustion plants

Figure 26: Plant profile for medium-sized combustion plants

Plant profile for medium-sized combustion plants

General data

Plant operator:	
Contact:	
Plant address:	

Plant-specific details

Date of commissioning (existing or new plant):	
Plant capacity in MW:	
Type of precipitator (fabric filter, electrostatic precipitator, etc.):	
Was a filter or electrostatic precipitator installed before 20 June 2029?	
Feedstocks (solid wood, chipboard, waste wood 1, waste wood 2, grain, etc.):	
Type of plant (boiler, steam boiler, combined heat and power, etc.):	
Industry:	

Source: Own illustration, Ramboll

C.2 Sampling protocol as part of the 'UBA POPs in Waste' project

Figure 27: Sampling protocol as part of the "UBA POP in Waste" project

Reference small combustion plant and samples:

1	**Plant**	P__ -______________________________
2	**Sample**	P__ -______________________________

Please enter the number of the plant and the location in the fields highlighted in blue

A. General details:

3	**Initiator / Client**	Ramboll Deutschland GmbH on behalf of the Federal Environment Agency
4	**Operator / Facility**	
5	**Postcode and town of the facility**	
6	**Reason for sampling**	Preliminary waste characterisation analysis
7	**Date of sampling (DD.MM.YYYY)**	
8	**Sampler / Department**	

B. Details of the boiler in question and the associated combustion plant:

	Type of boiler in question (relevant for sampling)	☐Hot water boiler ☐Steam boiler ☐Thermal oil boiler ☐Other: ______________
	Date of commissioning	Boiler in question: Firing system:
	Type of emission control technology for the boiler in question	☐Fabric filter ☐Ceramic filter ☐Electrostatic precipitator – wet precipitator ☐Electrostatic precipitator – dry precipitator ☐SNCR ☐Other:
	Date of installation of the filter in question:	
	Thermal output of the boiler in question and of the entire combustion plant (biomass boilers only; in MW)	Boiler in question: Total:
	Emission limit value for dust (for the boiler in question)	
	Oxygen reference value (11% according to TA Luft or 6% according to 44th BImSchV) (for the boiler in question)	

	Condition of the combustion plant, the boiler and the flue gas cleaning system in question	☐In working order ☐Defects Brief description of the defects:

C. General information on the fuel for the boiler in question:

	Fuel: Selection: Wood pellets Wood chips Wood from landscape management Production waste (solid wood, chipboard, etc.) Waste wood AI Waste wood AII Straw Cereals Other	Primary fuel used: Percentage: Secondary fuel used: Percentage: Other fuels:
	Fuel moisture	Fuel moisture content in %:
	Fuel quality – Suspected pollutants/hazards (if any)	
	Industry NACE code **(wood processing, heat generation, etc.)**	
	Testing laboratory	Eurofins GfA Lab Service GmbH, Am Neuländer Gewerbepark 4, 21079 Hamburg

D. Information on sampling:

Filter ash (filter residue)		
Sample identification:		
	General description of the sample (visual abnormalities/contaminants, e.g. unburned plastic parts, nails, etc.; if present, approximate percentage)	
	Quantity sampled (in g)	
	Duration of storage of the sampling material at the sampling point (time in days/weeks since the last emptying/cleaning)	
	Factors affecting the material at the time of sampling (if applicable (wet/dry, ...))	
	Sampling equipment and material	
	Description of sampling (if possible; collection of individual sample(s) using equipment, description of selection/collection from the total quantity present)	
	Number of individual samples (IS) (if feasible)	
	Sample preparation steps (if carried out)	
	Observations during sampling / comments (if applicable)	
	Photographic documentation: ***Please insert photos of the samples here***	

27 Test reports from the testing body (to be added by the client at a later date):

Coarse ash:

Sweepings:

Filter ash:

Source: Own illustration, Ramboll