Written by the Specialist Advisory Group (SAG):

Eulyn Pagaling (Chair)[1], Lucinda Robinson (Secretariat)[1], Michelle Bloor[2], Laura Carter[3], Efthalia Chatzisymeon[4], Stuart Harrad[5], Andreas Kolb[6], Martin Sharkey[7], Anna Stec[8], Zulin Zhang[1], Ioanna Akoumianaki[9], Lorna Dawson[9]

Affiliations
1. The James Hutton Institute
2. University of Glasgow
3. University of Leeds
4. University of Edinburgh
5. University of Birmingham
6. Rowett Institute, University of Aberdeen
7. University of Galway
8. University of Central Lancashire
9. SEFARI

Persistent Organic Pollutants (POPs) in Waste: Emerging Treatment Technologies

Scottish Government
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Contents

1. Introduction

Scotland's ambition to become a net zero and circular economy nation is underpinned by the recognition that material consumption and waste are primary drivers of climate and biodiversity pressures. Around four-fifths of Scotland's carbon footprint comes from the products we manufacture, consume and discard (Scottish Government, 2022). Reducing waste and moving resources higher up the waste hierarchy is therefore essential for meeting Scotland's obligations under climate and biodiversity targets (Scottish Government, 2025).

Persistent organic pollutants (POPs) present a particularly acute challenge. These synthetic chemicals have very long half-lives and bioaccumulate through the food chain (Gluge et al., 2020). They occur in a wide range of industrial and consumer products, from forever chemicals in electronics and furniture (such as brominated flame retardants) to textiles and firefighting foams (such per- and polyfluoroalkyl substances - PFAS).

Under the Stockholm Convention, POPs above regulatory thresholds must be destroyed or irreversibly transformed. In practice, the only option currently available in Scotland is high-temperature incineration at 800–900°C. This ensures destruction but prevents viable energy recovery, and thus undermines resource efficiency and sits uncomfortably with Scotland's circular economy ambition.

Objectives

This project seeks to address issues and challenges to the circular economy as posed by POPs by considering new and emerging technologies (or practices) that can either remove POPs from materials, allowing them to move up the waste hierarchy, or improve separation to ensure that the loss of resource is minimised. This was done through the following objectives:

1. Identify current and emerging technologies that could improve Scotland's ability to identify and separate POPs materials (including at waste collection and treatment centres).
2. Identify current and emerging technologies that could be used to treat waste/materials containing POPs, with an emphasis on moving material up the waste hierarchy.
3. Summarise the potential benefits and limitations of each technology (e.g. cost, carbon intensity) within a Scottish context, the range of materials that the technology may be applied to and suggest a 'Technology Readiness Level' for each technology assessed.
4. Drawing on international experience where applicable, and/or relevant experience from other technology sectors, identify opportunities for Scotland to create an effective R&D and implementation environment to drive progress in this area.

2. Research Undertaken

The review drew on a mixed approach using a literature review, a source-pathway-receptor model and a stakeholder workshop:

- Literature review: A rapid review of peer-reviewed and grey literature was undertaken to map the occurrence of POPs in Scottish-relevant waste streams and to identify technologies for identification, separation and treatment. Where data were lacking, estimates were drawn from England, Wales and the Republic of Ireland, which share similar regulations and waste streams (European Commission, 2019; ECHA, 2021; DEFRA, 2022).

- Source–Pathway–Receptor model: A Source-Pathway-Receptor (SPR) model was created as a way to conceptualise the main pathways by which POPs travel, disperse, and interact with the environment and potential receptors (Figure 1). The SPR conceptual model focused on POPs identified previously, namely polychlorinated biphenyl (PCBs), PBDEs, HBCDD, PFOS, PFHxS, PFOA and hexabromobiphenyl. A comprehensive assessment was carried out, placing particular emphasis on POPs present in contaminated solid waste. This focus was driven by the recognised need to develop effective strategies for recycling materials containing POPs while ensuring environmental safety and regulatory compliance.

- Stakeholder engagement: A workshop with representatives from research, policy and industry was held to validate findings and ensure practical realities were reflected.

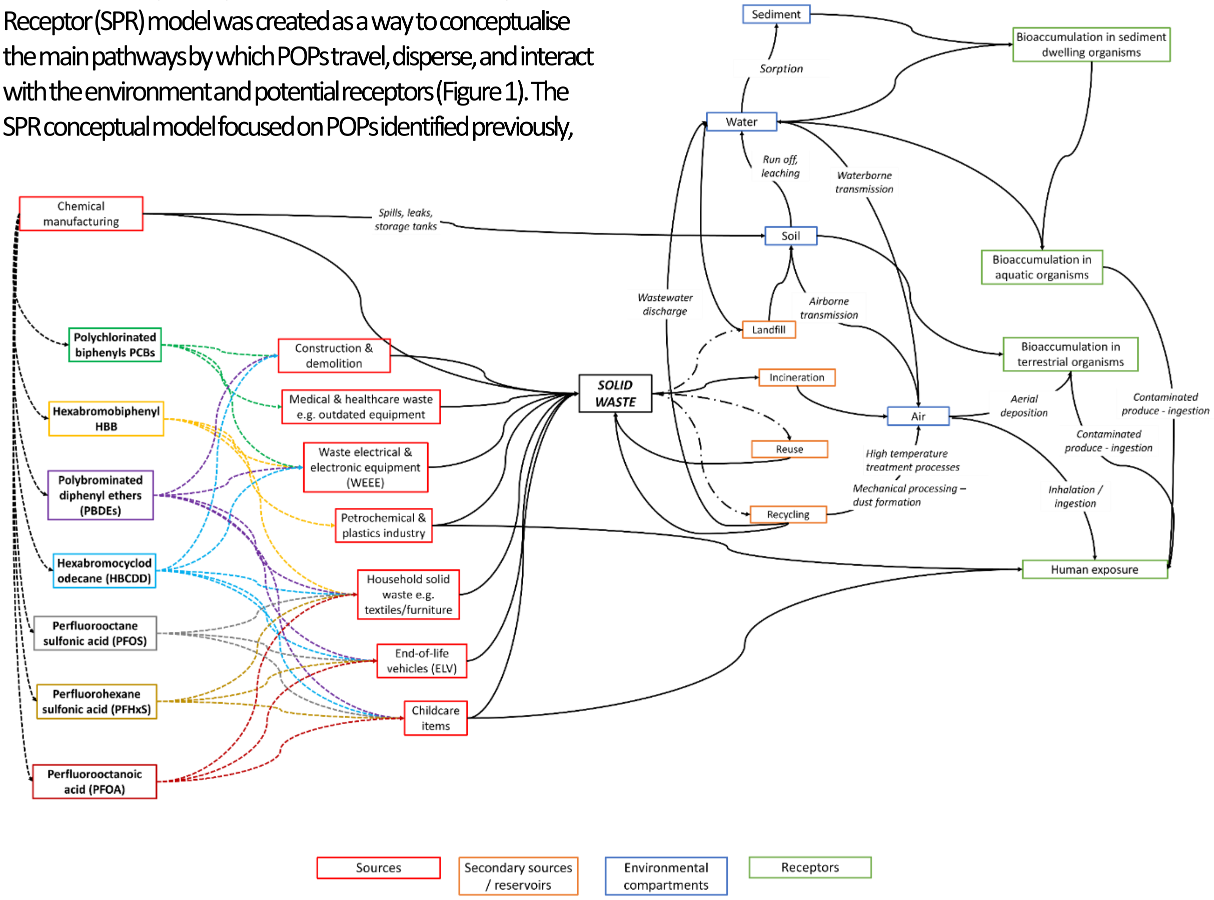

Figure 1. Source-Pathway-Receptor model to show how POPs travel, disperse, and interact with environment and potential receptors. Recycling and reuse pathways that move waste up the waste hierarchy are included. Accepted practices (e.g. incineration) are in solid line, and potential pathways if POPs waste is not managed correctly is in dash-dot line.

3. Results

3.1 Objective 1

POPs present in solid waste can enter the environment through a variety of pathways, depending on the disposal method used. Items containing POPs should not be safely disposed of in general waste. If solid waste containing POPs is disposed of into landfills, these chemicals can leach into nearby soils (Melnyk et al., 2015). Recycling POPs contaminated waste can introduce new environmental exposure pathways, potentially leading to unintended contamination.

Key pathways include:

1. Airborne Emissions
2. Water Contamination
3. Product Recontamination

The evidence review confirmed that several POPs remain widespread in products that are now reaching the waste stream. The main compounds of concern are brominated flame retardants such as PBDEs and HBCDD, and per- and polyfluoroalkyl substances (PFAS) including PFOS, PFOA and PFHxS. These substances are found in many everyday materials – from insulation boards and vehicle interiors to sofas, mattresses, carpets and electrical equipment (European Commission, 2019; DEFRA, 2022).

High concentrations are particularly associated with older furniture and electronics, where flame retardants were used extensively before restrictions were introduced (Harrad et al., 2019). This makes legacy waste a key challenge: once these products enter recycling or disposal, it becomes very difficult to separate POP-containing fractions from safe material.

At present, only a small number of tools exist to help waste operators identify and separate POPs. Density separation and handheld X-ray fluorescence (XRF) are the most advanced techniques. There is potential for sorting waste according to its known potential for contamination by POPs with density separation (Harrad et al., 2019). There have been significant limitations too. For example, XRF can detect bromine as a marker of brominated flame retardants but cannot identify which specific compounds are present (van der Veen and de Boer, 2012). As a result, waste managers often have to rely on broad assumptions rather than precise chemical data, which leads to precautionary incineration of entire waste loads.

Workshop insights

Stakeholders at the workshop reinforced the evidence as outlined above. Industry participants stressed that the chemical content of many imported or legacy products is unknown, making it risky to attempt recycling. Waste managers described the practical challenges of separating POPs at scale, especially when materials are composites such as foams bonded to fabrics. Policymakers highlighted the lack of rapid testing facilities in Scotland, which forces operators to treat mixed waste as contaminated and incinerate it rather than risk breaching regulations.

3.2 Objective 2: Treatment Technologies

The review identified a wide range of technologies being explored to treat or destroy POPs in waste. These fall into four main categories:

- Physical and chemical processes such as Creasolv®, which selectively dissolves plastics to separate them from POPs, and supercritical fluid extraction or microwave-assisted extraction. These approaches have shown promise in laboratory trials but remain expensive and limited in scale.
- Advanced oxidation methods, including photochemical treatments and hydrothermal oxidation, which use light, pressure or heat to break down persistent chemicals. These can be effective but are highly energy intensive.
- Thermal approaches, such as gasification, pyrolysis and smouldering combustion, which can destroy POPs while recovering energy. However, they risk producing toxic by-products if not tightly controlled.
- Biological methods, like bioleaching, have mainly been tested in electronic waste to recover valuable metals, with mixed results on POP breakdown.

Overall, the review found that only density separation, handheld XRF and Creasolv® have reached beyond laboratory trials towards commercial use. Most other technologies are still at early research stages.

Workshop insights

At the workshop, stakeholders were cautious about the cost and scalability of these technologies in a Scottish context. Policymakers questioned whether regulatory rules under the Stockholm Convention would even allow material recovery if POP levels were only reduced rather than completely destroyed. Researchers however saw potential to adapt existing technologies from other waste sectors, such as hydrothermal treatment to POPs if investment and pilot projects were supported.

3.3 Objective 3: Benefits and Limitations

Each of the technologies reviewed comes with clear benefits but also significant drawbacks. See Appendix for an all-encompassing review of benefits and limitations.

Benefits identified in the evidence review include the potential to:

- Reduce reliance on high-temperature incineration, which currently dominates POP disposal in Scotland.
- Recover valuable resources, particularly plastics and metals, that are otherwise lost.
- Support Scotland's circular economy and climate ambitions.

Limitations are equally important. Most technologies are still expensive and small-scale, with uncertain commercial viability. Some, such as pyrolysis generate toxic by-products that themselves require safe disposal. The strongest evidence of benefits comes from waste electrical and electronic equipment (WEEE), while there is much less evidence for furniture, textiles, or construction materials.

Workshop insights

In the workshop, stakeholders highlighted that while the theoretical advantages are attractive, Scotland lacks pilot facilities to test these technologies in practice. They also raised concerns about public acceptability of energy-intensive treatments, particularly if emissions and residues are not well understood. Policymakers stressed the need to demonstrate clear alignment with national policy goals before new approaches could gain support.

3.3 Objective 4: Barriers and Opportunities

The review pointed to a number of structural barriers. The most important is the strict legal requirement under the Stockholm Convention to destroy POPs above threshold levels, which leaves little room for material recovery. Other barriers include the technical difficulty of treating composite products, the lack of Scottish treatment infrastructure, and weak connections between research, industry and regulators, which slow down the pathway from laboratory to practice.

At the same time, several opportunities were identified. These include setting up verification laboratories in Scotland to support testing and innovation; developing digital product passports or chemical disclosure databases to improve transparency of material content; and commissioning feasibility studies to test promising technologies. International case studies suggest there may be some flexibility within the Stockholm Convention to trial innovative methods under controlled conditions.

Workshop insights

Workshop participants echoed these findings above. Waste managers emphasised the high cost of exporting POP-contaminated waste and the risks of relying on limited incineration capacity. Policymakers saw strong potential in product passports but noted the legal and practical hurdles in requiring industry disclosure. Researchers stressed the importance of cross-disciplinary collaboration, linking environmental chemistry with policy and industrial practice, to build a supportive innovation environment.

4. Recommendations

The review makes clear that Scotland's current reliance on high-temperature incineration is not sustainable if we are to meet our climate and circular economy goals. While incineration ensures destruction of POPs, it locks valuable resources out of circulation and undermines efforts to recover materials. Both the literature and the workshop discussions highlighted that Scotland is at an early stage in exploring alternatives, but also that opportunities exist to build momentum quickly if the right conditions are created.

A key theme across the evidence was the need for stronger cross-sector collaboration. Research alone will not deliver solutions. Industry, government and regulators need to be directly involved in shaping how technologies are developed and tested. Stakeholders stressed that Scotland lacks the infrastructure to trial new approaches, which means promising innovations stall at the laboratory stage. This creates a cycle where investment is hard to attract because no pilot facilities exist, and no pilot facilities exist because investment is lacking.

Investment in research and infrastructure will therefore be critical. Evidence suggests that technologies such as Creasolv® and hydrothermal oxidation could offer real benefits if they were scaled beyond pilot stage (Citations selected by the SAG). Workshop participants emphasised that without targeted funding, Scotland risks falling behind other European nations already trialling advanced treatment methods.

Another recurring message was the importance of chemical transparency. Waste managers and policymakers alike stressed that uncertainty about the chemical content of imported and legacy products is one of the main barriers to recycling. International experience shows that digital product passports and disclosure databases can give waste operators the confidence to separate and treat materials more effectively.

Finally, the review highlighted that Scotland should explore policy innovation within the framework of the Stockholm Convention. While the convention requires destruction of POPs above thresholds, there may be scope to pilot technologies under controlled conditions if compliance is maintained. Stakeholders agreed that Scotland could position itself as a test-bed for innovative but safe approaches, if the right regulatory dialogue is established.

Summary of Recommendations:

1. Strengthen engagement across research, industry and government to accelerate the translation of promising technologies into practice.
2. Increase investment in R&D and infrastructure for POP-containing waste streams.
3. Undertake feasibility studies of alternative technologies, assessing technical, economic and environmental performance.
4. Improve transparency by requiring mandatory disclosure of chemical content in products, supported by databases or digital product passports.
5. Enable policy innovation by identifying safe and compliant pathways for piloting alternative treatment methods.

5. Conclusion

Persistent organic pollutants (POPs) represent a major barrier to Scotland's circular economy ambitions. Current reliance on incineration is effective for destruction but wastes resources and prevents energy recovery. A range of emerging technologies show promise, but most remain in early development.

Scotland has an opportunity to lead internationally by integrating policy, research and industry, investing in innovation and improving product transparency. Without these steps, POPs will continue to remove valuable materials from circulation while posing long-term risks to health and the environment.

Evidence sources and references can be provided on request.

sefari.scot

info@sefari.scot

@SEFARIscot

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