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Integrated processing of heterogeneous waste plastics through controlled thermal consolidation and contaminant managementIntegrated processing of heterogeneous waste plastics through controlled thermal consolidation and contaminant management

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Research Article

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GFR PEER-REVIEW PAPER 1
COMPLETE WORKING MANUSCRIPT — WASTE MANAGEMENT SUBMISSION PREPARATION

Full-Scale Thermal Consolidation of Heterogeneous Mixed Plastic Waste with Reduced Preprocessing: A Resource-Recovery Case Study

ABSTRACT

Heterogeneous mixed-plastic waste is difficult to recover when conventional recycling depends on polymer separation, size reduction, cleaning, homogenisation and remelting. This study investigates a reduced-preprocessing resource-recovery pathway in which a full-scale, substantially unshredded industrial plastic-waste bale is subjected to prolonged, rate-controlled indirect heating and mechanical compression. The purpose-designed reactor applies upper and lower thermal input while mechanical loading progressively reduces void volume as thermally susceptible constituents soften. The experimental feedstock represented real industrial waste rather than a laboratory-formulated polymer blend, with nominal bale dimensions of approximately 1.20 × 1.20 × 0.75 m and an incoming mass range of approximately 500–750 kg. Full-scale trials demonstrated substantial vertical consolidation while retaining a visibly heterogeneous internal structure. Comparison between successive trials showed that thermal-input control influenced localised charring and consolidation uniformity, while the large feedstock geometry produced persistent heat-transfer limitations characteristic of bulk waste processing. The resulting solid material was sufficiently consolidated for mechanical cutting and further manufacturing evaluation without a second complete melting and reforming cycle. The results are presented as evidence of process feasibility rather than proof of batch-to-batch repeatability or final material performance. Feedstock variability, heat-transfer distance, temperature-control reliability, mass balance, energy demand and final material characterisation are identified as key variables for further investigation. The work contributes to solid-waste resource-recovery research by examining whether useful material value can be recovered directly from compositionally variable bulk plastic waste while avoiding selected preprocessing and feedstock-homogenisation stages.

Keywords: heterogeneous plastic waste; thermal consolidation; resource recovery; reduced preprocessing; industrial waste; waste valorisation

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Working manuscript reframed for Waste Management (Elsevier). Bake Test 2 results are reported where supported by recorded measurements. Exact proprietary processing duration and selected final dimensional details are withheld from the public manuscript.

1. Introduction

Plastic materials provide significant advantages in manufacturing, food production, packaging, transport and many other industrial applications. These same applications, however, generate large quantities of post-use plastic containing mixtures of different polymer types, product forms, contamination and residual materials. Such heterogeneous waste streams can be difficult to return to conventional material-recycling pathways.

Established mechanical recycling processes generally perform most effectively when feedstock composition is sufficiently controlled and contamination can be managed. Difficult mixed-plastic waste may therefore require combinations of sorting, washing, drying, shredding, separation, homogenisation, remelting and reforming before a new product can be manufactured. The additional processing required for highly heterogeneous material may increase equipment requirements, energy demand and process complexity while limiting the range of waste that can be practically recovered. [1–3]

This creates an opportunity to investigate whether a useful material can be produced without first attempting to convert heterogeneous waste into a conventional homogeneous recycled-polymer feedstock.

The Green Frog Revolution (GFR) research programme investigates a controlled thermal-consolidation approach in which substantially unshredded, heterogeneous and contaminated baled plastic waste is processed as a bulk material. The method applies prolonged, rate-controlled indirect heating in combination with mechanical compression. Rather than seeking complete homogeneous melting of the entire feedstock, the process investigates whether progressive thermal softening and reduction of internal void volume can consolidate the heterogeneous mass into a stable solid material.

An important feature of this approach is the scale at which thermal treatment occurs. A full compressed plastic bale represents a substantial three-dimensional insulating mass rather than the comparatively small particles, flakes or pellets typically associated with conventional polymer processing. Heat-transfer distance, internal thermal gradients, heating rate and duration of thermal exposure consequently become important experimental variables.

Observations from full-scale development trials indicate that attaining a particular reactor temperature does not necessarily result in immediate consolidation throughout the bale. Measurable consolidation may occur only after prolonged thermal exposure, and further consolidation has been observed after active heating has ceased. These observations provide the basis for investigating the role of thermal soak time, internal heat migration and retained thermal energy in the consolidation of large heterogeneous plastic masses.

The research also investigates whether the resulting consolidated material may itself become manufacturing stock. Rather than producing an intermediate recycled feedstock that subsequently requires another complete melting and forming operation, the consolidated block is intended to be mechanically cut or machined directly into finished or semi-finished products. If demonstrated, this approach may reduce selected preprocessing requirements and avoid a second complete thermal reforming cycle.

The broader GFR research programme includes additional investigations concerning recovered hydrocarbon-containing constituents, their controlled utilisation, combustion performance, emissions,

contaminant management and PFAS treatment and mineralisation. These research streams have distinct experimental and analytical requirements and are being investigated separately. Their exclusion from the present paper is therefore a deliberate separation of research scope rather than an absence of investigation.

This paper focuses specifically on the thermal and physical consolidation of heterogeneous mixed-plastic waste. It examines the experimental reactor configuration, thermal-treatment methodology, observed consolidation behaviour, heat-transfer characteristics and the potential for producing mechanically processable solid material from substantially unshredded mixed-plastic feedstock.

The objective of this Stage 1 investigation is not to establish final commercial performance or definitive material properties, but to determine whether the observed consolidation mechanism warrants continued systematic investigation and to identify the principal variables requiring measurement and control in subsequent instrumented trials.

2. Background and Problem Definition

2.1 The heterogeneous mixed-plastic waste problem

Plastic recycling is technically most straightforward when the waste stream consists of relatively clean, identifiable and compatible polymer materials. In practice, however, many commercial and industrial waste streams contain mixtures of different polymers, flexible films, multilayer materials, labels, closures, residual organic matter, moisture and other contaminants.

This heterogeneity presents a fundamental difficulty for conventional mechanical recycling. Different polymers exhibit different thermal and mechanical behaviours, while contamination and incompatible materials can affect the consistency and properties of the resulting recycled material. Consequently, recycling processes may require sorting, washing, drying, shredding or granulation, separation and feedstock homogenisation before the material can be remelted and formed into another product. [1–3]

These operations can increase processing complexity, equipment requirements, handling stages and energy consumption. For difficult or highly heterogeneous waste streams, the amount of preprocessing required may also reduce the practical or economic attractiveness of conventional recycling.

The problem addressed in the present research is therefore not whether relatively clean and homogeneous thermoplastics can be recycled. Such processes are already well established. The research instead considers whether useful material can be recovered from a substantially unshredded, heterogeneous and contaminated mixed-plastic waste stream using a less preprocessing-intensive approach.

2.2 Reconsidering the requirement for feedstock homogenisation

Conventional plastics manufacturing generally seeks a controlled and comparatively homogeneous feedstock because predictable material composition assists in controlling melting behaviour and final product properties. Mixed polymer streams can exhibit phase incompatibility and variable processing behaviour, which is a recognised challenge in mechanical recycling. [1–3]

The GFR research investigates a different processing objective.

Rather than attempting to transform heterogeneous waste into a homogeneous polymer feedstock before product manufacture, the process investigates whether the heterogeneous material itself may be progressively thermally softened and mechanically consolidated into a useful solid mass.

The objective is not necessarily to completely melt every constituent polymer or produce a material equivalent to virgin resin. Instead, controlled thermal energy is introduced over an extended period while mechanical loading progressively reduces void volume within the bale. Polymer constituents that soften under the imposed thermal conditions may deform and consolidate while the overall material remains visibly heterogeneous.

The resulting material can therefore retain evidence of its original heterogeneous composition rather than becoming a completely homogeneous melt.

2.3 The scale and heat-transfer problem

Processing a full compressed bale introduces a different engineering problem from heating shredded, pelletised or thin-section plastic material.

A densely packed heterogeneous plastic bale contains substantial internal void spaces and materials having different geometries, thermal properties and responses to heating. Plastic itself is generally a relatively poor conductor of heat, and the compressed bale can therefore behave as an insulating mass.

Consequently, reactor temperature alone may not adequately describe the thermal condition of the material.

Heat must migrate from the heating surfaces into progressively more remote regions of the bale. The outer, central, upper and lower regions may therefore experience different thermal histories even when exposed within the same reactor.

Experimental observations during the present development programme indicate that measurable consolidation may be delayed after elevated reactor temperatures have been achieved. Consolidation has also been observed to continue after active heating is discontinued.

These observations suggest that thermal exposure time, internal heat migration and retained thermal energy may be as important as peak reactor temperature in determining consolidation behaviour.

This creates an important process-control problem: increasing heat-input rate to accelerate processing may produce excessive temperatures and localised thermal damage near heating surfaces before sufficient thermal energy has migrated into more remote regions of the bale.

The process must therefore investigate a balance between heating rate, temperature, heat-transfer distance, thermal exposure time and mechanical consolidation.

2.4 Avoiding unnecessary repeated thermal processing

A further consideration is the number of processing stages required between receipt of waste material and production of a useful product.

Where recovered plastic is shredded, processed into an intermediate recycled feedstock and subsequently remelted to manufacture a product, thermal and mechanical processing may occur through multiple stages.

The present research investigates whether substantially unshredded mixed-plastic waste may instead undergo a primary controlled thermal-consolidation process that produces a solid material capable of being mechanically cut or machined into useful products.

If technically demonstrated, such an approach may avoid selected preprocessing operations and may remove the requirement for a second complete melting and reforming cycle.

The potential benefit is therefore not simply consolidation of waste volume. The research investigates whether the consolidated material itself may become the manufacturing stock from which products are produced.

2.5 Research problem

The central research problem addressed by this study can consequently be stated as:

Can heterogeneous, contaminated and substantially unshredded mixed-plastic waste be converted into a stable consolidated solid material through prolonged, rate-controlled indirect heating and mechanical compression without requiring complete homogeneous melting and subsequent remelting into a finished product?

Associated questions include how thermal energy migrates through a large heterogeneous compressed plastic mass; the relationship between heating rate, thermal exposure time and consolidation; whether consolidation continues after active heating ceases; whether sufficient consolidation can be achieved without unacceptable localised melting, charring or other thermal damage; how feedstock heterogeneity affects final material consistency; whether the consolidated material can be mechanically processed directly into useful products; and what material properties and batch-to-batch repeatability can ultimately be achieved.

2.6 Scope boundary

The present paper specifically addresses the thermal and physical consolidation of heterogeneous mixed-plastic waste. Hydrocarbon-containing volatile matter removed during thermal treatment is treated as a separate process stream within the broader GFR research programme.

The GFR research programme also encompasses the characterisation and controlled utilisation of recovered hydrocarbon-containing constituents, combustion performance, emissions, contaminant management and PFAS treatment and mineralisation. These areas involve distinct experimental methods, analytical requirements and validation pathways and are therefore being investigated and reported separately.

Their exclusion from the present paper represents a deliberate separation of research scope rather than an absence of investigation. This allows the present study to concentrate specifically on the thermal-transfer, consolidation and material-processing behaviour of heterogeneous mixed-plastic waste.

Thermal treatment of heterogeneous and contaminated plastic waste may generate gaseous and condensable process streams containing substances requiring environmental characterisation. The composition and mass of these streams, including the fate of contaminants potentially transferred from the incoming waste, have not been fully characterised in the present study. Consequently, successful consolidation of the solid fraction should not be interpreted as demonstrating that gaseous or condensable outputs are environmentally benign. Their composition, contaminant

content and environmental significance require separate analytical investigation and mass-balance assessment.

2.7 Waste-management relevance and study contribution

The present work is framed as a solid-waste treatment and resource-recovery investigation rather than as a product-development study. Its principal contribution is the evaluation of a reduced-preprocessing thermal-consolidation route for bulk heterogeneous industrial plastic waste. Downstream manufacture is relevant only insofar as it demonstrates a potential recovered-material pathway. Accordingly, the study focuses on feedstock composition and scale, process stages, thermal and mechanical treatment, consolidation behaviour, mass and energy accounting, operational limitations and the extent to which useful solid material value can be retained without complete feedstock homogenisation.

3. Bake Test 2 — Full-Scale Controlled Thermal Consolidation

3.1 Experimental purpose and evidence basis

Bake Test 2 was undertaken as a full-scale developmental trial to further investigate the thermal and physical consolidation behaviour identified during the preceding bake. The principal objective was to determine whether a substantially unshredded, heterogeneous industrial plastic-waste bale could be progressively softened and mechanically consolidated during a single controlled thermal-processing cycle while reducing the localised thermal damage observed during the earlier trial.

Observations from Bake Test 1 were used to inform the revised operating condition for Bake Test 2. In particular, localised upper-region charring observed under the earlier heating condition indicated that simply increasing local heat input was not an appropriate means of accelerating consolidation. Bake Test 2 therefore continued the investigation of prolonged, controlled heat input, thermal soak and heat migration through the bulk mass.

3.2 Full-scale industrial feedstock

The experimental feedstock was not a laboratory-formulated polymer mixture. It comprised bulk heterogeneous mixed-plastic waste obtained from an operating industrial waste stream and processed substantially in the physical form in which it was received and baled. The bale contained mixed plastic packaging materials together with items including plastic packing straps and baling twine. The material was not reduced to a homogeneous pellet, flake or powder feedstock before thermal consolidation.

Incoming compressed bales are approximately 1200 mm × 1200 mm × 750 mm. Because the waste is not sorted into a predetermined polymer formulation, bale mass is not fixed. Observed incoming bale masses are approximately 500–750 kg, with variation attributable to differences in material composition, residual moisture, contamination, packing configuration, void fraction and the relative proportions of individual constituents.

This variability is a deliberate part of the engineering problem being investigated. Feedstock variability is itself an experimental variable rather than a condition removed before experimentation.

Correspondingly, the dimensions, mass, apparent density and internal composition of the outgoing consolidated blocks are expected to vary between trials. A fixed final block mass or geometry is therefore not assumed. Initial and final dimensions and mass are recorded for each trial so that the degree of consolidation can be evaluated against the actual feedstock processed.

3.2.1 Physical movement and photographic chain of evidence

Photographic documentation was retained as part of the experimental record to establish the physical scale, movement, handling and transformation of the feedstock. The image sequence

records an incoming compressed plastic bale, multiple bales loaded for road transport, a full bale positioned within the GFR reactor, the post-processing consolidated material after cutting, and sections removed from the consolidated block. The sequence therefore provides a visual chain of evidence from bulk feedstock movement through reactor loading, thermal consolidation and subsequent mechanical cutting.

The road-transport image is included specifically as documentary evidence of physical plastic movement. It shows multiple compressed bales being transported as bulk material and demonstrates that the feedstock was handled as a transportable industrial waste stream rather than being assembled as small laboratory-prepared specimens adjacent to the reactor. This evidence is relevant to interpretation of scale because the reactor trial concerns the handling and processing of hundreds of kilograms of heterogeneous material per bale.

The photographs are not used as substitutes for quantitative measurements. They establish feedstock form, physical handling, scale, visible consolidation and machinability. Mechanical strength, chemical stability, environmental performance and durability require separate quantitative testing and are not inferred from visual appearance.

(a) Incoming compressed heterogeneous plastic feedstock bale

(b) Multiple compressed bales loaded for road transport

(c) Full-scale bale positioned within the GFR reactor

(d) Consolidated block exposed after processing and cutting

(e) Sections cut from consolidated heterogeneous material

Figure 3.1. Physical progression of heterogeneous plastic feedstock through the GFR thermal-consolidation process. (a) Example incoming compressed bale; (b) multiple bales transported as a bulk material stream, providing documentary evidence of physical plastic movement; (c) full bale positioned within the experimental reactor; (d) consolidated material following thermal processing and cutting; and (e) cut sections demonstrating formation of mechanically processable solid material. Feedstock was processed without polymer-specific homogenisation, and variations in bale mass, dimensions, moisture, contamination and material composition were retained as experimental variables representative of the real-world waste stream.

3.3 Physical scale and initial apparent bulk density

For a nominal incoming bale measuring 1.20 m × 1.20 m × 0.75 m, initial bulk volume is:

$$V_i = L_i W_i H_i = 1.20 \times 1.20 \times 0.75 \approx 1.08\ m^3$$

Using the observed incoming mass range of approximately 500–750 kg:

$$\rho_i = m_i / V_i \approx 463–694\ kg\ m^{-3}$$

These values demonstrate the physical scale of the experiment. The reactor is required to transfer heat through approximately one cubic metre and hundreds of kilograms of compositionally variable, partially insulating material rather than through a small or compositionally controlled specimen.

3.4 Thermal processing and Bake 1 to Bake 2 development

The reactor applies indirect thermal input from upper and lower heating assemblies while mechanical loading acts on the softening bale. The process does not seek to establish a rapid homogeneous melt. Instead, susceptible constituents progressively soften while void volume is reduced and the heterogeneous mass consolidates.

Bake Test 2 produced visibly more uniform treatment across the observed upper surface than Bake Test 1 and substantially less localised charring. This observation supports continued investigation of controlled heat-input rate and extended thermal exposure rather than increasingly aggressive local heating.

External reactor-wall measurements during relevant periods were approximately 55–60 °C. These measurements are reported only for the measured reactor location and are not interpreted as the internal temperature of the plastic core. The large bale behaves as a three-dimensional insulating mass and may contain substantial internal thermal gradients.

Periods of limited measurable dimensional movement followed by later consolidation are consistent with the working hypothesis that thermal migration and soak time contribute to progressive softening. Previous observations of additional consolidation after electrical heating was discontinued further support investigation of retained internal thermal energy and post-heating redistribution. The mechanism has not yet been quantified by three-dimensional internal temperature measurement.

3.5 Temperature-control anomaly

A thermostat malfunction was subsequently identified during Bake Test 2. This is recorded as an equipment-control anomaly and experimental limitation rather than being omitted from the record. The event does not establish the internal temperature history of the bale, and no unsupported internal-temperature value is inferred from it. Subsequent reactor development replaces the affected control arrangement with electronic temperature control.

The presence of the control anomaly is considered when interpreting Bake Test 2. Direct observations of consolidation, surface condition and measured temperatures remain reportable, while causal conclusions dependent on an assumed temperature history are treated cautiously.

3.6 Dimensional consolidation and density mathematics

Initial and final volumes for each trial are calculated as:

$$V = LWH$$

Vertical consolidation is calculated as:

$$C_h = ((H_i - Hf) / H_i) \times 100$$

Where complete dimensional measurements are available, volumetric consolidation is:

$$C_v = ((V_i - Vf) / V_i) \times 100$$

Apparent bulk density before and after processing is:

$$\rho_i = m_i / V_i \qquad \text{and} \qquad \rho f = mf / Vf$$

The density-increase ratio is:

$$R\rho = \rho f / \rho_i$$

These relationships allow consolidation to be compared between bales without assuming that heterogeneous feedstock must produce an identical final block geometry. Final Bake Test 2 mass and dimensions are to be reported from the post-cycle measurements and inspection record rather than inferred from previous trials.

3.7 Mass balance

$$m_i = mf + mrecovered + munaccounted$$

$$MR = (mf / m_i) \times 100$$

Complete mass closure is not claimed unless all outgoing streams are independently measured. Differences between incoming and final block mass may include residual moisture removal and evolution of volatile constituents and therefore must not automatically be attributed to polymer decomposition.

3.8 Gross process-energy accounting

$$ER = PR \times D \times t$$

where ER is gross reactor electrical energy, PR is installed electrical heating power, D is effective heater duty factor and t is operating time.

$$SECfeed = ER / mfeed$$

Electrical energy for the experimental reactor was supplied by a diesel generator. The broader GFR system provides for recovered combustible reactor gases to be supplied to the generator as a supplementary fuel stream. The present study reports gross reactor electrical demand and does not assign an energy credit to recovered gases because gas composition, energy content, substitution rate and net energy contribution have not yet been independently quantified.

3.9 Single-cycle consolidation finding

Bake Test 2 provides further evidence supporting the feasibility of converting substantially unshredded heterogeneous industrial plastic waste into consolidated solid material through one thermal-processing cycle. The resulting material is intended to be mechanically cut or machined directly into finished or semi-finished products rather than being converted into an intermediate feedstock requiring a second complete melting and reforming operation.

This result should not yet be interpreted as proof of batch-to-batch repeatability. For heterogeneous feedstock, repeatability should ultimately be assessed by determining whether variable incoming bales repeatedly produce material within defined ranges of consolidation, density, structural integrity and manufacturability, rather than by requiring every bale to produce an identical final dimension.

3.10 Solid constituents and environmental interpretation

Non-polymeric and other solid constituents not removed from the heterogeneous feedstock may remain physically incorporated within the consolidated material. The potential for the consolidated polymer matrix to immobilise or encapsulate such constituents, and its resistance to release through leaching, weathering or mechanical degradation, requires specific environmental testing and is not established by the present study.

3.11 Relationship to contemporary waste-recovery research

Recent research demonstrates broader engineering interest in developing practical pathways for recovering useful manufacturing materials from heterogeneous and difficult waste streams. One contemporary example is the MIT-led CERBERUZ research undertaken within NASA's LunaRecycle Challenge, which investigates an integrated architecture incorporating waste preparation, material recovery and subsequent manufacture of useful products. [4]

Although CERBERUZ was developed for a substantially different operating environment and employs cleaning, sorting, size reduction, separation and remanufacturing processes that differ from the present approach, the research illustrates the broader relevance of engineering systems intended to recover usable material value from complex waste streams. The present GFR investigation contributes to this developing field by examining a different processing question: whether real-world bulk, substantially unshredded heterogeneous industrial plastic waste can be thermally softened and mechanically consolidated directly into solid manufacturing stock while avoiding selected preprocessing and feedstock-homogenisation stages.

3.12 Interpretation of experimental scale

Laboratory-scale investigations remain essential for identifying mechanisms and evaluating new processing concepts under controlled conditions. Demonstration of a mechanism at small scale, however, is distinct from demonstrating throughput, energy requirement, process stability and material tolerance at industrially relevant scale. The present study therefore reports the physical size and mass of the incoming feedstock together with the resulting consolidated material so that the reader can evaluate the experimental result in the context of the quantity and variability of waste actually processed.

3.13 Bake Test 2 reporting status

Final Bake Test 2 mass and exact final dimensions are not reported in the present manuscript. No values are inferred from previous trials. Accordingly, final apparent density, mass-retention percentage and exact dimensional-consolidation values are not calculated here. Qualitative observations are reported only where supported by the completed trial record. This preserves the distinction between measured evidence, proprietary process detail and quantities requiring a complete publication-ready measurement record.

Table 1. Full-scale feedstock and Bake Test 2 reporting framework

Parameter	Current value/status	Evidence treatment
Incoming bale dimensions	Approx. 1200 × 1200 × 750 mm	Observed full-scale feedstock geometry
Incoming bale mass	Approx. 500–750 kg	Variable with moisture and material composition
Nominal initial volume	Approx. 1.08 m^3	Calculated
Initial apparent bulk density	Approx. 463–694 kg/m^3	Calculated from nominal geometry and observed mass range
Feedstock preparation	Substantially unshredded; no complete homogenisation	Experimental method
Bake 2 surface outcome	More uniform treatment; substantially less localised charring than Bake 1	Visual observation

Measured external wall temperature	Approx. 55–60 °C during relevant periods	Location-specific measurement; not core temperature
Temperature-control anomaly	Thermostat malfunction identified	Recorded experimental limitation
Final Bake 2 dimensions	Not reported in this manuscript	Exact final dimensional detail withheld; do not infer
Final Bake 2 mass	Not reported in this manuscript	No final mass, density or mass-retention value inferred
Repeatability	Not yet demonstrated	Requires equivalent subsequent trials

3.14 Scope boundary for Waste Management submission

This paper does not claim finished-product certification, polymer-specific recycling efficiency, contaminant destruction, fuel performance, PFAS mineralisation, life-cycle superiority or commercial-scale repeatability. These matters require separate experimental programmes. Paper 1 is limited to the full-scale solid-waste treatment and resource-recovery question demonstrated by the reported thermal-consolidation trials.

3.15 Emissions, PFAS analytical evidence and scope limitation

Thermal treatment of heterogeneous and contaminated plastic waste can generate gaseous and condensable process streams in addition to the consolidated solid fraction. Within the broader GFR research programme, reactor-derived gas can be directed to a diesel generator fitted with the Combustion System Enhancement Technology (CSET), and an associated water stream has been sampled for PFAS analysis. These investigations are relevant to the wider contaminant and emissions mass balance, but they are analytically distinct from the solid-waste thermal-consolidation experiment reported in this paper.

In March 2026, a water sample associated with the GFR CSET system and diesel generator was independently collected by an occupational hygienist using laboratory-supplied sterile bottles. The generator hour meter recorded 13,236.9 operating hours at the time of sampling. Envirolab analysed the sample under Certificate of Analysis 404075. The selected PFAS analytes shown in the certificate were reported below their applicable practical quantitation limits (PQLs), with the associated quality-control information documenting method-blank, laboratory-control-sample and matrix-spike results.

This downstream analytical result must be interpreted within an important limitation: a matched laboratory-tested pre-CSET sample was not obtained as part of the March 2026 investigation. Accordingly, the result establishes the measured condition of that downstream water sample only. It does not establish a percentage PFAS reduction, PFAS destruction efficiency or PFAS mineralisation. Demonstrating those outcomes requires controlled matched pre- and post-treatment sampling together with appropriate analysis of relevant gaseous, condensable, aqueous and solid streams and a defensible contaminant mass balance.

The same evidentiary boundary applies to emissions more broadly. Successful consolidation of the solid fraction and a non-detect or below-PQL result in a downstream water sample do not demonstrate that gaseous or condensable process outputs are environmentally benign. Further

work must identify the composition and mass of these streams, quantify potentially toxic constituents, and determine contaminant fate across the complete process. For this reason, the PFAS evidence is included here as supporting evidence from the broader emissions and contaminant-management programme, not as proof of PFAS mineralisation by the Bake Test 2 consolidation process.

4. PFAS Analytical Investigation and Results

4.1 Generator / CSET Installation and PFAS Water Sampling

The PFAS water sample was independently collected in March 2026 from the water tank associated with the GFR CSET system and diesel generator. The generator had accumulated 13,236.9 operating hours at the time of sampling.

(a) GFR CSET system integrated with diesel generator (genset). Gas feed from reactor to CSET and exhaust outlet indicated.

(b) Generator hour meter showing 13,236.9 operating hours at the time of PFAS water sampling.

(c) PFAS water sampling point at the rear of the generator. Sample collected by Occupational Hygienist using laboratory-supplied sterile bottles (IOHC, March 2026).

Figure 4.1 *Generator / CSET installation and PFAS water sampling (March 2026).*

4.2 Envirolab Certificate of Analysis – PFAS Results (Certificate No. 404075)

The PFAS water sample was analysed by Envirolab, a NATA-accredited laboratory. The selected PFAS compounds were reported below their applicable practical quantitation limits (PQLs).

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Client Reference: IOHC260311

POLYFLUORINATED ALKYL SUBSTANCES (PFAS) in water

Our Reference	Your Reference	Date Sampled / Time	PFBS µg/L	PFHxS µg/L	PFOS µg/L	PFOA µg/L	6:2 FTS µg/L	8:2 FTS µg/L	Total Positive PFAS µg/L
404075-1	IOHC260311-1	21/03/2026 10:40	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01

PQL = Practical Quantitation Limit.
All results in µg/L (micrograms per litre).
PFBS = Perfluorobutanesulfonic acid
PFHxS = Perfluorohexanesulfonic acid
PFOS = Perfluorooctanesulfonic acid
PFOA = Perfluorooctanoic acid
6:2 FTS = 6:2 Fluorotelomer sulfonate
8:2 FTS = 8:2 Fluorotelomer sulfonate
Total Positive PFAS = Sum of PFAS detected at or above laboratory PQLs.

Figure 4.2 *Envirolab Certificate of Analysis 404075 – PFAS results. All selected PFAS compounds reported below applicable PQLs (see Section 4.3 for QA/QC summary).*

ENVIROLAB SERVICES — **CERTIFICATE OF ANALYSIS 404075** — Page 5 of 13

QUALITY CONTROL RESULTS

Method Blank

Analyte	Result (µg/L)	PQL (µg/L)
PFBS	<0.01	0.01
PFHxS	<0.01	0.01
PFOS	<0.01	0.01
PFOA	<0.01	0.01
6:2 FTS	<0.01	0.01
8:2 FTS	<0.02	0.02
Total Positive PFAS	<0.01	0.01

Laboratory Control Sample (LCS)

Analyte	Spike (µg/L)	Recovery (%)	Acceptance Criteria (%)
Total Positive PFAS	0.10	95	70 – 130

Matrix Spike (MS)

Analyte	Spike (µg/L)	Recovery (%)	Acceptance Criteria (%)
Total Positive PFAS	0.10	92	70 – 130

QA/QC performed in accordance with laboratory procedures and NATA requirements.

Figure 4.3 *QA/QC summary from Envirolab Certificate 404075, including method blank, laboratory control sample (LCS) and matrix spike (MS) results within acceptance criteria.*

Important Note: A matched pre-CSET laboratory-tested sample was not obtained as part of the March 2026 investigation. Accordingly, these results represent a measured downstream analytical condition only and do not establish a percentage PFAS reduction or demonstrate PFAS mineralisation. Further controlled pre-/post-CSET experiments are required (see Sections 5, 11 and 12).

Figure 3.2. Supporting PFAS and emissions-related evidence from the broader GFR research programme. The composite records the generator/CSET installation and reactor-gas feed, generator operating hours at sampling, the

PFAS water sampling point, and selected pages from Envirolab Certificate of Analysis 404075 and its QA/QC summary. The March 2026 downstream water result is not a matched pre-/post-CSET experiment and therefore is not evidence of percentage PFAS reduction or PFAS mineralisation.

4. Conclusions

Bake Test 2 provides full-scale developmental evidence that a substantially unshredded, heterogeneous industrial mixed-plastic waste bale can undergo substantial thermal and mechanical consolidation through a single controlled processing cycle. The trial also indicates that heat-transfer distance, thermal exposure time, feedstock variability and temperature-control reliability are important process variables at this scale. More uniform observed treatment and reduced localised charring relative to the preceding trial support continued investigation of controlled heat input and extended thermal exposure rather than aggressive local heating. The resulting solid material provides a basis for further manufacturing evaluation, but the present study does not establish batch-to-batch repeatability, certified material performance, complete mass closure, contaminant immobilisation, emissions safety or life-cycle superiority. Further instrumented trials should quantify three-dimensional temperature histories, final mass and dimensions, energy demand, volatile and condensable outputs, contaminant fate, material properties and repeatability. The central contribution of this Stage 1 work is therefore the demonstration of a full-scale reduced-preprocessing resource-recovery pathway sufficiently promising to justify systematic validation.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author used ChatGPT (OpenAI) to assist with manuscript organisation, language refinement and literature-search support. The author reviewed and edited the content and takes full responsibility for the content of the publication.

References

[1] Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. Waste Management 69, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044
[2] Schyns, Z.O.G., Shaver, M.P., 2021. Mechanical Recycling of Packaging Plastics: A Review. Macromolecular Rapid Communications 42, 2000415. https://doi.org/10.1002/marc.202000415
[3] Muzata, T.S., Matuana, L.M., Rabnawaz, M., 2024. Challenges in the mechanical recycling and upcycling of mixed postconsumer recovered plastics (PCR): A review. Current Research in Green and Sustainable Chemistry 8, 100407. https://doi.org/10.1016/j.crgsc.2024.100407
[4] Etzenbach, L., McKinney, L., Patel, P.B., Soto, J., et al., 2025. Modular Waste Recycling and Manufacturing System Architecture for the Moon and Beyond. 76th International Astronautical Congress, Sydney, Australia. https://doi.org/10.52202/083078-0034