# Recycling Solutions for Remote and Regional Communities in the Northern Territory: Demonstration of Microrecycling for Multilayer Packaging Waste

IP2.02.02 Finding Fit for Purpose Technological Recycling Solutions for Regional and Remote Communities

# Demonstration of case study 1 - Remote Community Project Progress Report

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The Sustainable Communities and Waste Hub acknowledges all Aboriginal and Torres Strait Islander Traditional Custodians of Country and recognises their continuing connection to land, sea, culture, and community. We pay our respects to Elders past, present, and emerging. We support Aboriginal and Torres Strait Islander peoples and their aspirations to maintain, protect and manage their culture, language, land and sea Country and heritage.

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## Executive Summary

The present study deals with the identification of various wastes generated in different region of the Northern Territory (NT) and investigate their recycling opportunities as a part of the circular economy integration in waste management approach. In line with 2018 National Waste Policy (NWP) framework and National Waste Policy Action Plan-2019, this case study provides the insight of existing waste management scenario and a case of recycling of multilayer packaging waste.

The primary data of this report collected through the extensive review of earlier literature. Along with findings from earlier studies, experimentation and characterisation was done for multilayer packaging waste, which is one of the most generated wastes but difficult to recycle, under different processing parameters to understand the scope of resource recovery out of it.

As the growing waste volumes pose escalating environmental and social challenges to all over Australia, so the adoption of their mitigation strategy is a timely demand approach. Out of the NSW and Victoria where waste management practices are more common, focus should be given to other areas e.g. Northern Territory as implementation of waste management approaches to those locations face challenges. It is worth mentioning that waste generated in NT is difficult to measure due to many reasons including the lack of weighbridges, infrastructure issues, data tracking etc.  in remote communities. The volumes of various waste streams largely depend on population sizes and distance from major towns. While recyclables are sorted and stockpiled, lack of information/skills/resources/financial incentives to manage the next steps in the reprocessing pathway are still a significant barrier. Although there is little or no information on the rates and volumes of the generation of waste, the current study list out various waste streams in the remote communities of the Northern Territory and conducted experiment to recycle one of them.

Primary waste categories include car batteries, tyres, scrap metal, car bodies, oil and paints, e-waste, cardboard, containers under the container deposit scheme, construction and demolition waste, mattresses and timber pallets. The volumes of various waste streams largely depend on population sizes and distance from major towns. While recyclables are sorted and stockpiled, lack of information/skills/resources/financial incentives to manage the next steps in the reprocessing pathway are still a significant barrier. Based on existing literature, our observations for future research are as follows:

- Conducting fieldwork to acquire actual data aimed at understanding the waste flow from generation to disposal.

- Categorise the waste with more preference to be given on recyclables

- Adoption of effective recycling techniques to recover resources from recyclables

- Finding the best routes for effective disposal of non-recyclable waste

One of the outcomes of this case study is the demonstration of Thermal Disengagement Technology (TDT) as a fit-for-purpose microrecycling solution for multilayered aluminium–plastic packaging waste, one of the most difficult yet widespread waste categories in the NT. By applying controlled heating in an inert atmosphere, TDT efficiently separates polymers from aluminium, enabling the recovery of high-purity aluminium (approximately 99%) and valuable carbon by-products, while also generating cleaner gases that can be repurposed for energy. Unlike conventional smelting, which often results in metal loss and higher energy demand, TDT offers a resource-efficient and environmentally sustainable pathway for complex waste. Its adaptability, small-scale design, and ability to be deployed locally make it particularly well suited to the challenges of remote and regional communities, offering a practical model for safe circularity and value creation from waste.

*Project Alignment and Contribution:* This case study aligns closely with the goals of the IP2.02.02 project, *"Finding Fit-for-Purpose Technological Recycling Solutions for Regional and Remote Communities."* It highlights how decentralised microrecycling systems—particularly Thermal Disengagement Technology (TDT)—can convert complex waste streams like multilayer packaging into valuable materials,which is one of the major concern of NT. The outcomes offer a tangible example of applying circular economy principles in regional areas of Australia, delivering both environmental benefits and community-focused outcomes.

**Keywords:** Northern Territory (NT); Remote and regional communities; Waste characterisation; Waste streams analysis; Circular economy; Microrecycling; Multilayer packaging waste; Thermal Disengagement Technology (TDT); Aluminium–plastic separation; Resource recovery; Decentralised recycling; Fit-for-purpose technologies; Waste management challenges; Recycling opportunities; Environmental sustainability.

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# 1. Introduction

With six key directions and sixteen priority waste strategies, the National Waste Policy (NWP) set by the Council of Australian Governments provides a comprehensive action plan mitigating the looming threats of various waste generated in different areas of Australia. The 2018 NWP applies principles of circular economy to waste management for better use of resources. The proposed circular economy notion suggests the transition from conventional linear 'make-use-dispose' culture to 'make-use- reuse' culture is expected not only to bring savings but also reduce negative impact on the natural environment [1, 2]. Heading towards the waste management solution in regional and remote Australia, a number of case studies conducted in various locations have been compiled and published by Regional and Remote Australia Working Group (R & RAWG) in the year of 2013 [3] highlighting the challenges in managing waste and recovering and re-using resources, solutions that have been tried and tested, including projects that have not been successful. Out of them all, two projects were completed in northern territory where the first project titled as "Lajamanu container deposit scheme pilot" was conducted by Centre for Appropriate Technology (CAT) and trialled a pilot container deposit scheme at Lajamanu in the Central Desert Shire, Northern Territory. It aimed to reduce the number of beverage containers sent to landfill, enhance community cleanliness; act as an incentive for collection or separation of beverage containers, reduce burning at landfill, promote some community ownership of waste management outcomes and return income to the community via the sale of recyclables, this project was designed for 1000 inhabitants. Through government funding, instruments were purchased and financial incentives given to collect waste (10c for aluminium cans and Polyethylene terephthalate (PET) bottles). Although, several challenges were faced, the outcome of this project is worthy to mention collecting 96,840 cans and plastic bottles were with refunds of $9,684 to community members where about 80 community members participated to make it successful. The second project titled as "Nhulunbuy waste disposal site redevelopment" was established on the Gove Peninsula in north-east Arnhem Land for the population size of 4500. Funded by Nhulunbuy Corporation Ltd and implemented by Gumatj Waste Management Pty Ltd, this project focused on the redevelopment of a poorly managed landfill to an award-winning

landfill and recycling centre. Waste batteries, tyres and steel were the main waste categories considered in this project which emphasised collection, minimizing pollution and shredding as the first phase of the project. Another independent case study was conducted by Deepika Mathur [4] in five distinct council wards - Kakadu (includes Jabiru), Gunbalanya, Maningrida, Minjilang and Warruwi through the interviews from employees of West Arnhem Regional Council who provides waste services to these communities. Landfill operations are initiated by garbage collection through garbage compactor truck and then tipped at a designated spot or in the trench followed by burning to reduce volumes. Wastes are collected through various streams, and the largest waste stream varies on geographic location and population. For instance, Gunbalaya reported general waste as its largest waste stream where construction waste is the primary waste for Jabiru and cardboard from the store was for Minjilang and Warruwi.
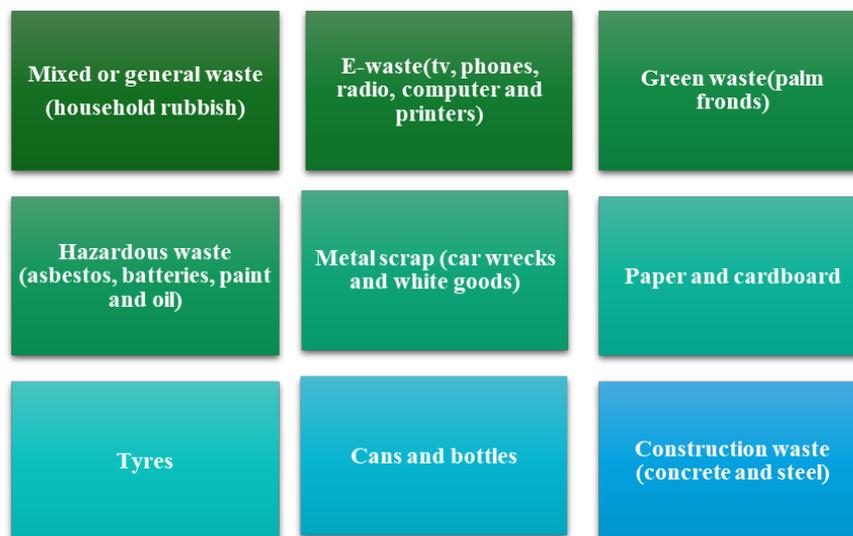


Figure 1: Types of waste identified in the study location [4]

It is worth mentioning that, out of the many wastes emerged from various waste streams; multilayered polymer-aluminum packaging waste is one of the most problematic waste categories due to their complexity in recycling.

Aluminum is widely used in packaging (with the plastics laminated in single or multi layers), from food and beverages to pharmaceuticals, foils, trays, lids, capsules, and containers. Its popularity comes from its excellent barrier properties—it resists corrosion and blocks oxygen, moisture, oils, microorganisms, ultraviolet light, and other external factors [5]. For sensitive products, aluminum is especially effective because it is hygienic, non-toxic, non-tainting, and preserves flavor and freshness[6]. Recycling aluminum also provides major environmental benefits: it requires only 5% of the energy and produces just 5% of the

emissions compared with producing primary aluminum [7]. However, because of the plastic lamination and thin layers, it is extremely difficult to recycle and often goes to landfills.

## 1.1 Alignment with Project Objectives

The overarching aim of this project is to identify and demonstrate scalable, fit-for-purpose recycling technologies that address waste management challenges in regional and remote areas, particularly Northern Territory of Australia. This case study exemplifies how TDT can be adapted to local waste types and logistical conditions. By integrating scientific characterisation with field insights, the study establishes a model that can guide the deployment of small-scale recycling systems across other remote communities in Australia.

## 2 Waste profile of different regions in NT
### 2.1 Northern Territory waste policy framework

Since the states and territories hold self-authority to prepare their own pathway to deal with waste considering the local case, they are not therefore bound to implement the NWP. The Circular Economy Strategy (2022-2027) published by the NT government adopts a whole-of-government approach, leverages opportunities identified across Government's priority areas and responds to current and emerging national and local drivers around waste. It recognises the unrealised value of materials currently being discarded into landfill or the environment.

Although the Northern Territory does not have any specific quantitative targets specified in its waste strategy [8], its strategies are focused on engagement and education, improving waste management (with a focus on container deposit scheme, and developing and consolidating recycling infrastructure), improving waste data collection, monitoring and analysis, improving the regulatory framework and reporting and public reviews [9].
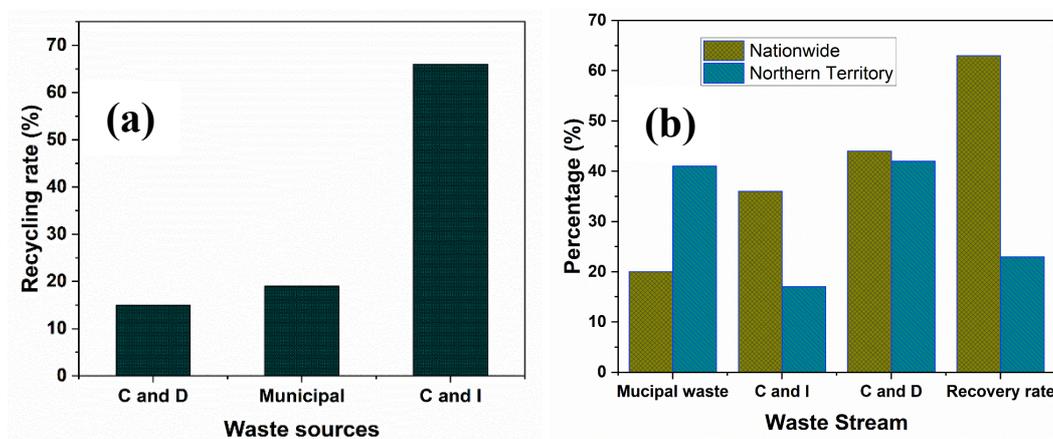
Figure 2: (a) Amount of waste generation from three different sectors, (b) comparative data between Northern Territory and Nationwide for various waste stream and recovery rate [10, 11]



Figure 3: (a & b)- Waste collection depots (Photo courtesy of the Centre for Appropriate Technology), (c & d) Renovated waste collection depots (Photo courtesy of Nhulunbuy Corporation Ltd), (e) Waste collection flow from local communities by regional council (Curtesy by Deepika Mathur)

Through the Northern Territory's Waste Management and Pollution Control Act 1998 (WMPC Act), guidelines for waste operators and landfill are controlled. Updated strategic

framework published in 2022 includes data collection, knowledge sharing, staffing, identification of priority waste streams and investments on landfill operations that align more closely to the national framework emphasising the integration of circular economy approach in its waste management process.

Population size, geographical factors, distances between population centres, weather conditions and waste infrastructure are some mentionable factors that collectively impact waste reduction, collection and waste processing [9]. In addition, transportation costs, low volume, absence of resource recovery infrastructure and staff management pose significant challenges in dealing waste in remote areas [3, 12].

## 2.2 Waste infrastructure in the Northern Territory

While around 60% of the population of the Northern Territory has access to some kerbside collection, the majority from remote and regional areas do not, particularly residents outside of the City of Darwin [13]. The 2020 national data shows that majority of recyclable materials are collected from commercial and industrial sources while less amount is contributed by construction sector [14].

Through the container deposit scheme (CDS), collection depots were established with the financial assistance from the Environment Grants Program [3, 15]. A significant momentum was recorded through the Territory-wide Plastic Bag Ban program initiated in 2011 which contributed to reduce more than 10 million bags in its first 4 years[9] . The facilities for sorting and processing waste are limited to a single reprocessing unit in Darwin (Shoal Bay) and multi-purpose processing units in Katherine, Tennant Creek and Alice Springs. Unlike the Western Australia where major portions of waste glass is used locally in road construction, the processing infrastructure is not available in NT resulting in glass waste being transported to Adelaide or Melbourne [11]. More than 70% of wastes generated in Northern Territory are discarded to landfill, much attention should be given to its negative consequences on people and environment. In 2015, the Northern Territory's Environmental Protection Agency (NTEPA) raised concerns about the conditions of regional landfills and waste facilities, and potential environmental and health impacts from the burning and burial of household waste [9]. Later, significant actions were taken by the active engagement of regional councils in managing landfills [10].

Presently, metal, polymer, and paper-based packaging dominate, and these can be recycled through smelting, pyrolysis, or chemical processing. In some cases, they are repurposed through physical transformation, such as incorporation into composite products. Packaging

materials that cannot be recycled are typically managed through landfilling or incineration, and in certain instances, they are used in waste to energy conversion.

## 2.3. Multilayered Packaging material

Multilayered metal–plastic laminated packaging waste is among the most difficult materials to recycle. For the case study on the Northern Territory, we focused our research on this type of packaging waste. Usually, Aluminium is laminated with plastics for multilayered packaging. The plastic layer strengthens the packaging while also improving protection against light, moisture, gases, and UV rays. Laminated aluminium provides higher flexibility and mechanical strength than aluminium alone, although this sometimes reduces properties such as transparency and permeability [16]. In many cases, industries use multilayer plastic films—produced through lamination or co-extrusion—because combining different polymers creates superior mechanical, chemical, and physical performance [17].

Despite these advantages, recycling aluminium–plastic packaging remains difficult. Separation of multiple plastic layers is complex, and extrusion recycling is further complicated by incompatibility among different polymers [18, 19]. For instance, PET requires higher processing temperatures than PP or PE, making mixed polymer recycling a challenge.

Aluminium–plastic packaging also resists reuse due to differences in material behavior under various conditions. However, because the plastics are primarily composed of carbon and hydrogen, multilayer aluminium packaging waste (MAPW) has a high calorific value [20]. This makes it possible to recover both metal and energy from such waste, offering benefits in waste reduction, energy generation, and aluminium reclamation.

Conventional recovery processes include smelting and chemical depolymerization (hydrolysis, glycolysis, alcoholysis) [21, 22], but these often result in aluminium losses. Other thermal methods such as gasification, molten salt treatment, and pyrolysis under oxygen-free conditions can recover valuable metals or stabilize hazardous ones at 600–800°C [23]. Successful recovery depends largely on process conditions. In oxygen-rich atmospheres, aluminium oxidizes and forms aluminium oxide, releasing significant heat during the reaction, as shown in Equation 1 ($\Delta H°298K = 1675.7$ kJ/mol) [24, 25]-

$$4Al + 3O_2 \rightarrow 2Al_2O_3 \ (1)$$
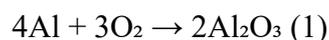
To minimize oxidation and recover metallic aluminium effectively, processes must be carried out in an inert atmosphere with a constant supply of protective gas. However, recycling post-consumer aluminium–plastic packaging remains limited due to the challenges of separating the two materials.

This case study presents Thermal Disengagement Technology (TDT) of Microrecycling as a sustainable approach to aluminium–plastic recycling. Microrecycling technology offers a small-scale, local approach that can be set up directly within communities, including remote or regional areas, unlike traditional large, centralised recycling plants. It uses modular systems that can be tailored to specific waste streams such as plastics, glass, textiles, or electronic waste, making it highly adaptable. By enabling on-site transformation, it converts waste directly into valuable materials or products, cutting down on the high costs and logistical challenges of transporting waste to distant facilities. Importantly, it supports safe circularity, ensuring that recycling processes don't simply downcycle waste but instead generate high-quality, safe outputs that can be reused effectively within the community.

TDT applies controlled heating in inert atmospheres to separate aluminium from plastics without smelting. The process enables recovery of high-purity aluminium while also producing cleaner gases from polymer breakdown. The innovative aspect of this case study is that TDT recycles aluminium at lower temperatures without metal loss, making it resource-efficient and environmentally sustainable. Plastics decompose into gases such as $CO$, $CO_2$, $H_2$, and hydrocarbons, which suppress aluminium oxidation and can be converted into useful fuels like methane and hydrogen. These gases can also provide heat for other processes. By fully utilizing both recovered aluminium and clean fuel gases, TDT offers a recycling pathway that is technically effective, commercially viable, and environmentally sound.

## 3. Identification and treatment of Multilayered Packaging Waste

Discarded multilayer aluminium packaging waste was collected from local sources and shredded into smaller pieces to remove residual contents from the packaging material. Collected samples consisted of aluminium foil laminated with polymers on both sides.

The as collected was characterized by Fourier-transform infrared spectroscopy (Spotlight 400 FT-IR, PerkinElmer) with an integrated attenuated total reflectance (ATR) unit and a thermogravimetric analyser (TGA, STA8000, PerkinElmer) at 800°C under nitrogen flow of 20 ml/min and constant heating rate of 20°C/min to study the chemical and thermal behavior of multilayered aluminium packaging waste (MAPW). The infrared spectrum resolution was 4 cm$^{-1}$ with wave number range between 650 and 4000 cm$^{-1}$.

Next to characterization in raw form, thermal disengagement of MAPW samples was carried out in a horizontal tube furnace (HTHTF50, ABB) under the flow of argon gas at 1 L/min for the periods of 10, 20 and 30 minutes at three different temperatures 400°C, 500°C, 600°C and

650°C. Emissions of thermal disengagement was measured by horizontal tube furnace (HTF7060, Radatherm) coupled with an IR gas analyser (AO2020, Advance Optima, ABB) where CO, $CO_2$, and $CH_4$ are detected. Following each treatment, the metallic residues and carbonaceous by-products were collected for further analysis.

Table 1: List of experimental characterization with respect to forms of the samples

| Characterizations | Forms of the samples | Identification |
|---|---|---|
| FTIR | Raw | Chemical nature |
| SEM | | Layer structure |
| **SEM EDS** | | Compositional mapping |
| TGA | | Thermal degradation |
| XRD | Thermal threated | Internal morphology |
| XPS | | Elemental imaging |
| FTIR | | Chemical nature |
| FE-SEM | | Surface morphology |
| Carbon and sulphur analyser | | Carbon content |
| LIBS | | Quality and elemental composition |
| ICP-MS | | |
| EBSD | | Phase and texture analysis of recovered metal |

Obtained Aluminum and solid co-products from the thermal disengagement process were analysed using an X-ray diffraction system (Empyrean, PANalytical) with a cobalt anode. The chemical states and elemental composition of the recycled aluminium surface were examined by X-ray photoelectron spectroscopy (XPS, Thermo ESCALAB250Xi), which provides both depth profiling and elemental imaging capabilities using an aluminium Kα X-ray source. Surface morphology and elemental distribution of the aluminium and co-products were further characterized by field emission scanning electron microscopy (FE-SEM, Nano SEM 450, FEI Nova). Amount of carbon was quantified using a LECO CS230 carbon and sulfur analyzer. Moreover, the quality and elemental composition of the recycled aluminium were assessed by laser-induced breakdown spectroscopy (LIBS Analyzer, SciAps, AXT) and inductively coupled plasma mass spectrometry (ICP-MS). Microstructural Analysis of the recovered aluminium was conducted by EBSD.

## 4. Findings

## 4.1 Characteristics of raw MAPW

The physical, chemical and thermal evaluation of the experimental samples through respective testing identifies their various properties.

The Fig.4 illustrates the microstructural characterization of a multilayered beverage packaging material. The left digital image shows the intact packaging, while the right image presents a high-resolution Scanning Electron Microscopy (SEM) cross-sectional view of the multilayered packaging. The SEM image clearly reveals a well-defined multilayer structure, typical of such packaging systems, consisting of distinct layers with varying contrast— indicative of different materials such as polymers, aluminum foil, and adhesives. Arrows highlight key features such as interfacial regions, layer separation, and crack propagation paths, which are critical for understanding the mechanical behavior and failure mechanisms within the structure. This analysis provides valuable insight into the layers and the structural integrity of the packaging, which is essential for performance optimisation and end-of-life treatment strategies like thermal or mechanical recycling.
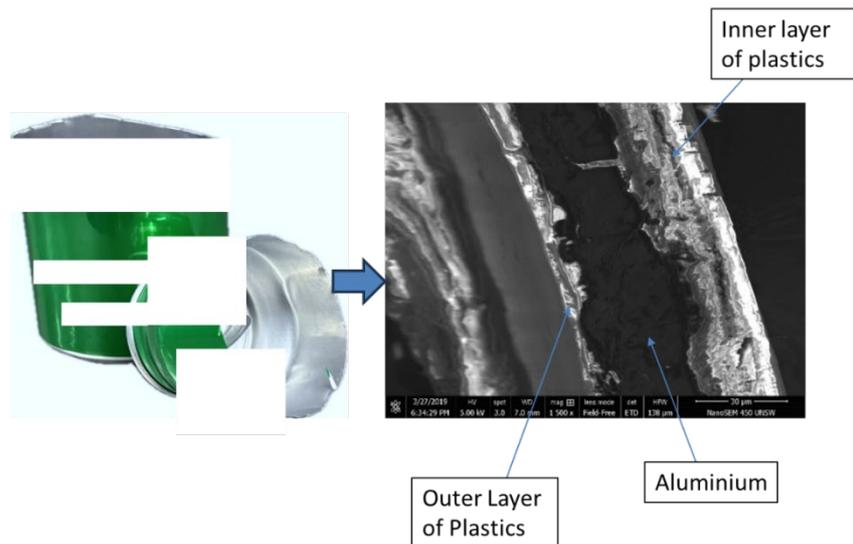


Figure 4: Cross-Sectional SEM Analysis of Multilayered Beverage Packaging Material

The cross-sections of layered structure observed by SEM measured the thicknesses of each layer. The thickness of inner layer was approximately ~15.26 μm, middle layer was of ~28.55 μm (aluminum), and the outer layer was ~15.41 μm.

The chemical nature of inner and outer layers was determined by Fourier-transform infrared spectroscopy (FTIR). Characteristic peaks (Fig.5) for inner layer were observed at 3300 cm$^{-1}$ for O-H stretching and C-O stretching at 1200-1100 cm$^{-1}$. For outer layer, peaks were observed by strong C+O stretching at 1720 cm$^{-1}$, and C-O-C ester group stretching at 1250-

100 cm$^{-1}$. Peaks at 2953–2850 cm$^{-1}$ was obtained for strong C–H stretching vibrations of alkanes for both layers.
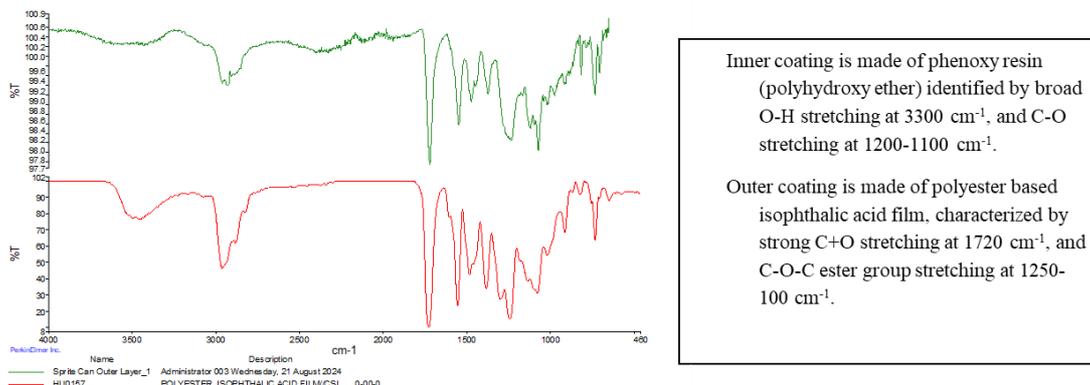


Inner coating is made of phenoxy resin (polyhydroxy ether) identified by broad O-H stretching at 3300 cm$^{-1}$, and C-O stretching at 1200-1100 cm$^{-1}$.

Outer coating is made of polyester based isophthalic acid film, characterized by strong C+O stretching at 1720 cm$^{-1}$, and C-O-C ester group stretching at 1250-100 cm$^{-1}$.

Figure 5: FTIR Spectral Analysis of MAPW showing the polymers in the inner and outer layer

As MAPW contains polymeric layers, the initial decomposition was noted at 300–480°C where almost all polymer decompose [26], Overall, the process resulted in a weight loss of ~30.01%. The heat flow curve highlighted two endothermic events: one near 450°C, corresponding to polymer decomposition, and another near 675°C, associated with the melting of aluminum.
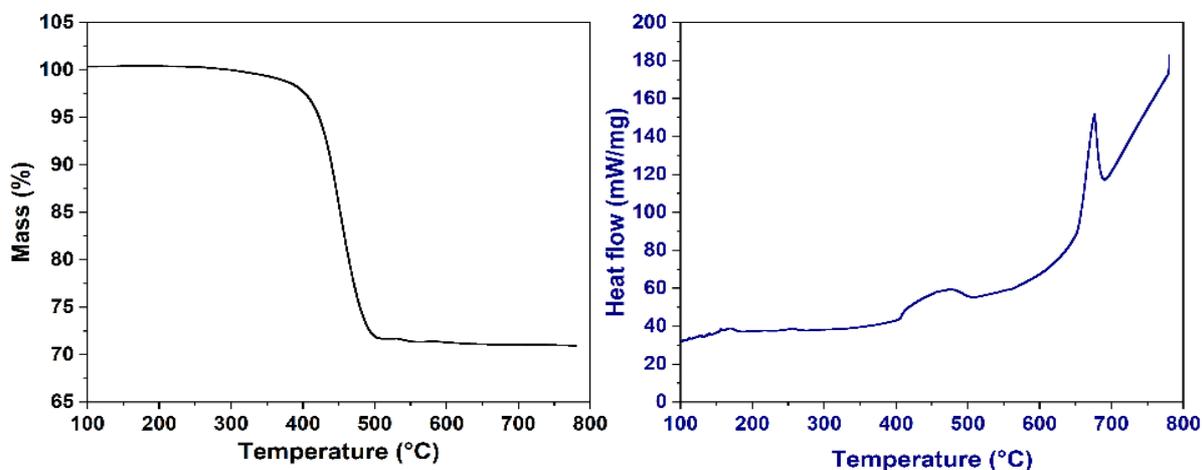


Figure 6: Thermal Characterization of MAPW via TGA and DSC Analysis. The left graph shows the Thermogravimetric Analysis (TGA) curve, indicating the mass loss of the multilayer packaging sample as a function of temperature. A significant weight loss occurs between 400–500 °C, corresponding to the thermal degradation of polymer components. The right graph presents the Differential Scanning Calorimetry (DSC) curve, revealing thermal transitions such as endothermic and exothermic events. Notable transitions are observed between 500–750 °C, indicating structural or compositional changes in the multilayer

material. These analyses help assess the thermal stability and composition of the packaging system.

## 4.2 Characteristics of treated MAPW

TDT of MAPW was conducted in a horizontal tube furnace with a continuous argon flow (1 L/min) to maintain an inert atmosphere at temperatures of 400°C, 500°C, 600°C and 650 °C. To determine optimum operating conditions, MAPW samples were treated at 10, 20, and 30 minutes. Volatile release began at ~300°C, consistent with TGA and FTIR observations. However, effective removal of polymer residues from aluminum required higher temperatures and longer residence times. Considering volatile release, residue removal, aluminium melting, and product quality, 600°C was identified as the optimal temperature.

The evaluation of released gas with the help of infrared gas analyser coupled with furnace revealed that volatile concentration varies with respect to time and temperature. The completion of thermal decomposition was shifted reduced when the temperature changed to higher temperature i.e. 600°C to 650°C. All gas concentrations increased steadily with temperature. Thermal cracking of hydrocarbons happened at elevated temperatures, where methane reacts with $CO_2$ or water vapor to form CO and $H_2$, as shown below [56]:

$$CH_4 + H_2O \rightarrow H_2 + CO \text{ (I)}$$
$$CH_4 + CO_2 \rightarrow H_2 + CO \text{ (II)}$$
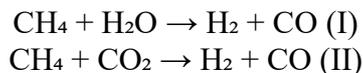
Thus, hydrocarbons initially formed by polymer scission and cracking [27] were subsequently reformed into CO and $H_2$ by secondary reactions with water and $CO_2$ [28].
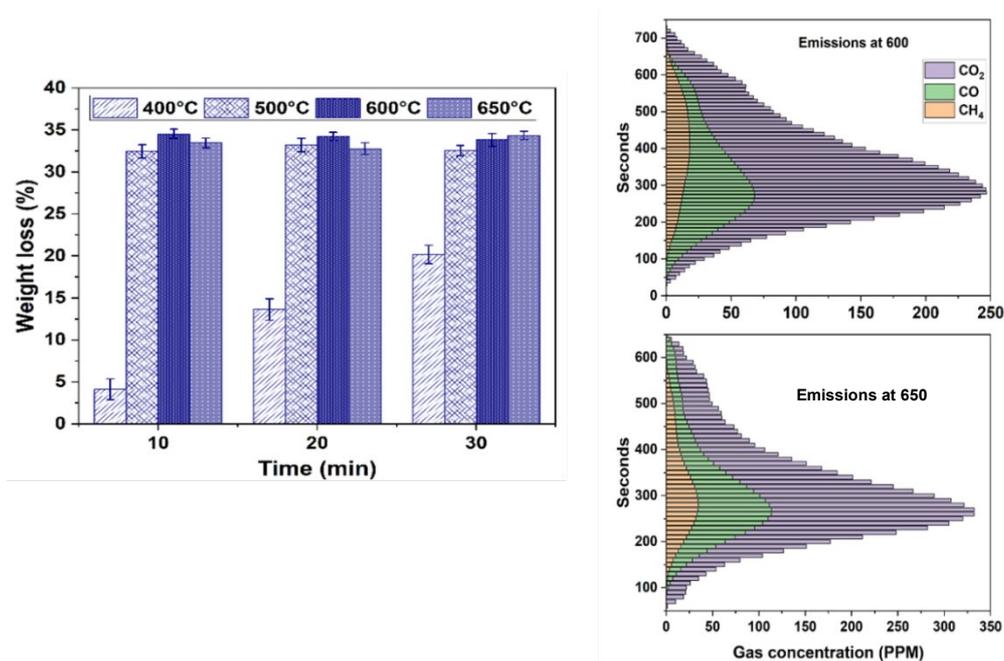
Figure 7: Thermal Degradation and gas emission behaviour of multilayer packaging material. The left panel illustrates the weight loss (%) of the multilayer packaging material over time (10, 20, and 30 minutes) at different pyrolysis temperatures (400–650 °C). A significant increase in weight loss is observed with both time and temperature, indicating progressive thermal degradation. The right panel presents gas emission profiles at 600 °C and 650 °C, showing the release of $CO_2$, CO, and $CH_4$ over time. Higher temperatures result in increased concentrations of gaseous byproducts, particularly $CO_2$, highlighting the thermal decomposition pathways and volatile compound evolution from the packaging matrix.

Surfaces of MAPW after treatment at 400°C, 500°C, 600°C and 650°C was tested. and obtained three main absorbance regions for all: 3135–2780 cm⁻¹, 1700–1400 cm⁻¹, and 1000–650 cm⁻¹. The thermally transformed sample at 600 and 650°C is demonstrated in Figure 8. These peaks indicate residual polymer fragments remaining on the aluminum surface. Longer exposure times and higher temperatures accelerated polymer bond scission, leading to noticeable reductions in peak intensity. Residual bands near 3044 cm⁻¹ correspond to C–H stretching in alkenes (CH, $CH_2$, $CH_3$ in sp² and sp³ configurations), while smaller peaks below 3000 cm⁻¹ represent asymmetric $CH_2$ stretching in aliphatic chains [29]. The 1605 cm⁻¹ peak reflects C=C vibrations of cyclic aromatic hydrocarbons[29], which diminish as polymer residues decompose further. At higher treatment conditions, a prominent ~940 cm⁻¹ peak emerges, attributed to Al–O bonds ($Al_2O_3$) [30]. This peak was absent at lower

treatment conditions, indicating that oxidation (likely due to trace oxygen in argon) occurred only after polymer layers detached from aluminium.
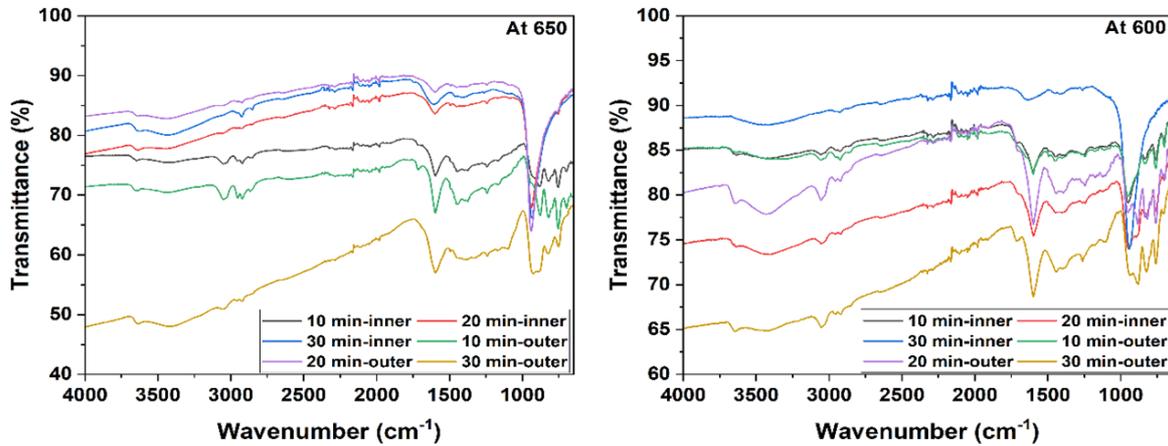


Figure 8: FTIR Spectral Comparison of Inner and Outer Layers of Multilayer Packaging After Thermal Treatment at 600 °C and 650 °C

The ATR-FTIR could measure down to 650 cm$^{-1}$, but no clear silicon-related peaks were distinguished in this lower range [31]. The X-ray Diffraction (XRD) pattern (Fig. 9) displays the phase composition of a multilayered material following thermal treatment for 15 minutes (black curve) and 30 minutes (red curve). The x-axis represents the diffraction angle (2θ), while the y-axis indicates intensity (counts), corresponding to the abundance and crystallinity of various phases.

Strong diffraction peaks observed at approximately 45° and 78° 2θ are attributed to crystalline aluminum. These peaks become significantly more intense after 30 minutes of thermal exposure, suggesting an increased presence of exposed aluminum metal, likely due to the degradation or removal of overlying layers.

Si–O (Silicon–Oxygen) peaks indicate the presence of silica-based components, likely originating from barrier layers or inorganic additives in the packaging.

Broad, low-intensity peaks in the low-angle region (~10–30° 2θ) are characteristic of amorphous polymeric materials. These peaks are more prominent in the 15-minute sample and are substantially reduced or flattened in the 30-minute spectrum, indicating thermal decomposition or structural breakdown of the polymer matrix over time.

Although the polymer peak is not clearly visible in the XRD spectrum after 15 minutes of thermal exposure at 600 °C, a more in-depth analysis using Rietveld refinement revealed that trace amounts of polymer remain. This analysis confirmed the presence of polymeric material in quantities below 1-2%, indicating incomplete decomposition at this stage.

As thermal exposure increases (from 15 to 30 minutes at 600 °C), the polymer components degrade further, resulting in diminished amorphous signals and enhanced visibility of the underlying or embedded pure aluminum metal alloy. The growing intensity of crystalline peaks supports this degradation pathway and highlights the transformation in material composition under elevated temperatures. The FE-SEM image of the treated sample shows the presence of carbon residue and recovered aluminium part as exhibited in Fig.10.
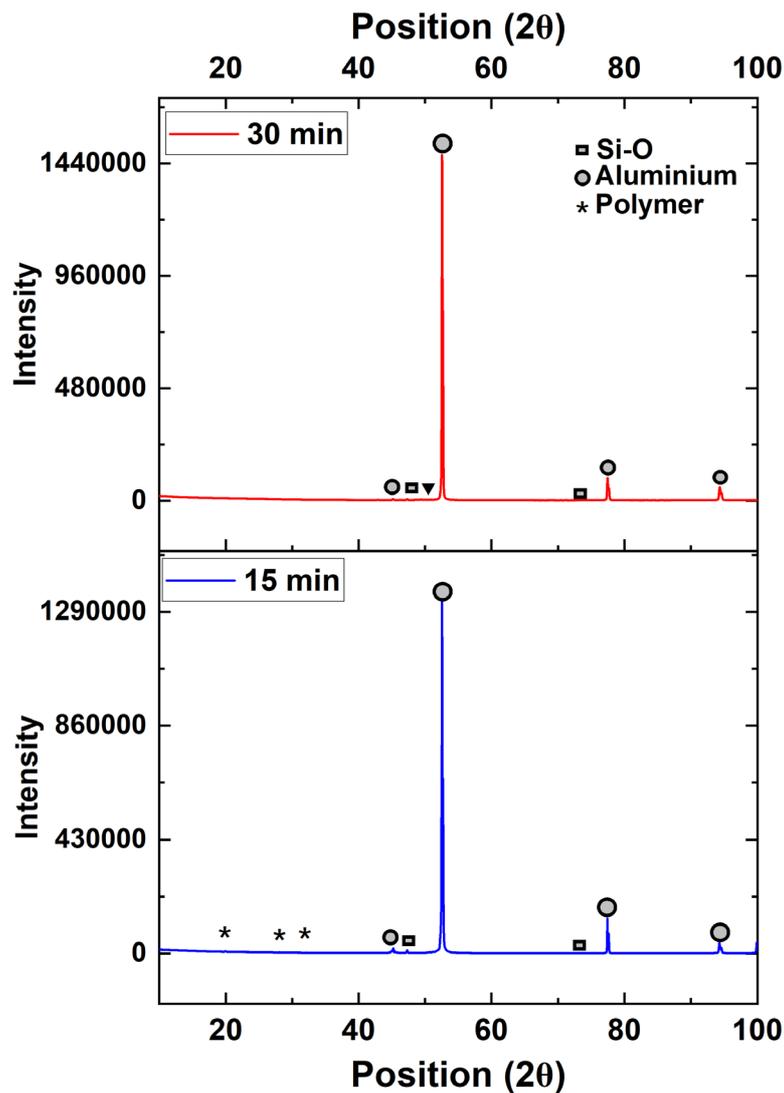


Figure 9: XRD Analysis of Multilayer Packaging Material after Thermal Treatment at 600 °C

Two types of products were obtained from the TDT of MAPW materials which are- pure aluminium metal alloy and carbon residues. The carbon fraction was measured to be approximately 3 wt% using a LECO CS230 analyser.

In Fig.11, the carbon residues originate from the thermal decomposition of the polymer matrix during processing and are not chemically bonded to the aluminum surface. Minor

traces of silicon are also detected, likely originating from inorganic additives or coatings in the original multilayer structure. This analysis confirms that the thermal treatment of the MAPW material effectively recovers a high-purity aluminum alloy while leaving behind superficial, non-integrated carbonaceous residues from the degraded polymer layers. This carbon automatically removes and can be separated and collected.
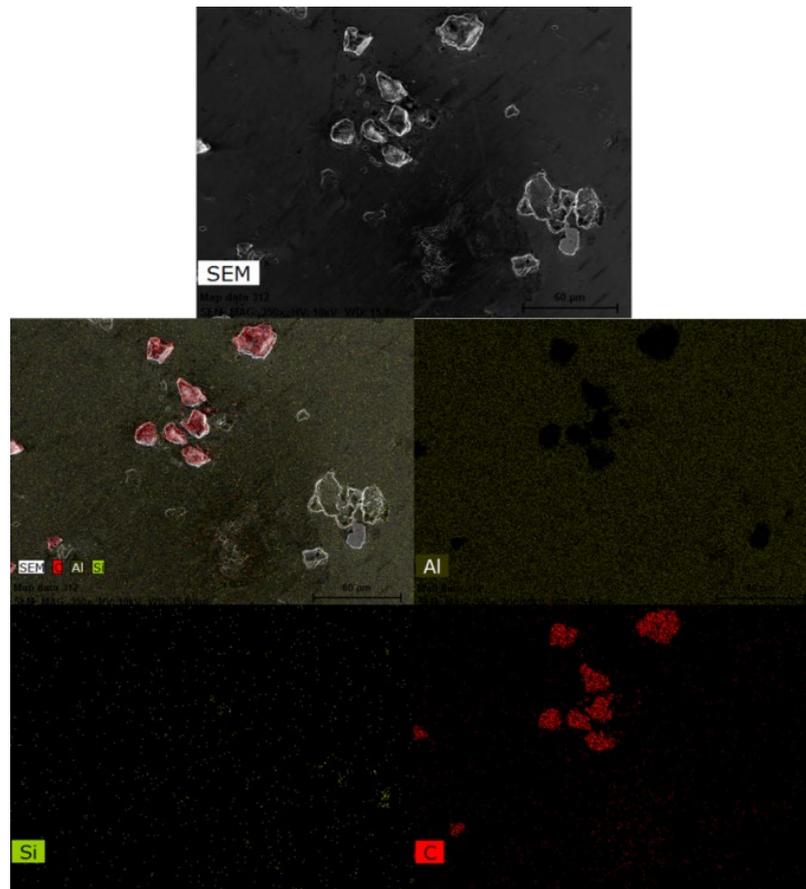


Figure 10: Recovered aluminium after the TDT process. Carbon residues are visible on the surface. The recovered aluminium is approximately 99% pure, with no signs of oxidation.
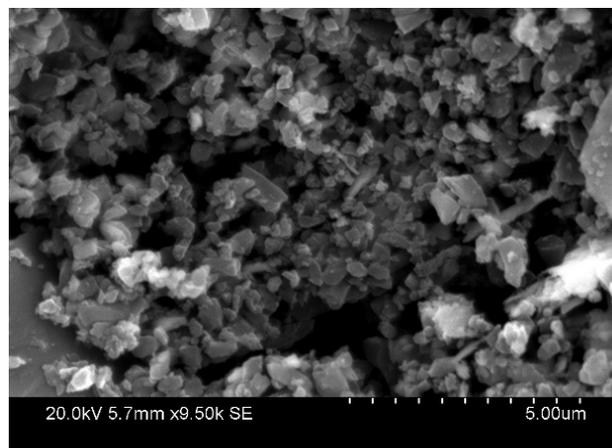


Figure 11: SEM image of recovered carbon

The composition of the recovered aluminium was analysed further through inductively coupled plasma mass spectrometry (ICP-MS) and laser-induced breakdown spectroscopy (LIBS). The results indicate that the recycled aluminium achieved a purity of around 99% in both techniques. The presence of silicon is attributed to the surface of the MAPW during TDT is either from the micro alloying element or from additives.

Table 2: Quality of the recovered Al alloy by LIBS

| Recovered al alloy | Experiment 1 | Experiment 2 | Experiment 3 | Experiment 4 | Experiment 5 | Avg. | Error |
|---|---|---|---|---|---|---|---|
| AL | 99.3 | 99.1 | 99 | 98.7 | 98.8 | 98.98 | 0.238747 |
| MG | 0.00751 | 0.00607 | 0.00356 | 0.00234 | 0.0049 | 0.004876 | 0.0020333 |
| SI | 0.095 | 0.099 | 0.422 | 0.498 | 0.513 | 0.3254 | 0.2113339 |
| ZN | 0.117 | 0.077 | 0.07 | 0.067 | 0.077 | 0.0816 | 0.0202688 |
| TI | 0.00323 | 0.013 | 0.00329 | 0.019 | 0.012 | 0.0101004 | 0.0067977 |
| FE | 0.532 | 0.653 | 0.479 | 0.629 | 0.498 | 0.5582 | 0.0783955 |
| SN | 0.0143 | 0.0321 | 0.00237 | 0.0101 | 0.0109 | 0.0139544 | 0.0110443 |

Microstructural Analysis of the recovered aluminium by EBSD is explained as follows-

a. Grain Boundary and Shape: Number of Grains: 878, Average Diameter: 37.92 micron, Equivalent ASTM No: 6.8



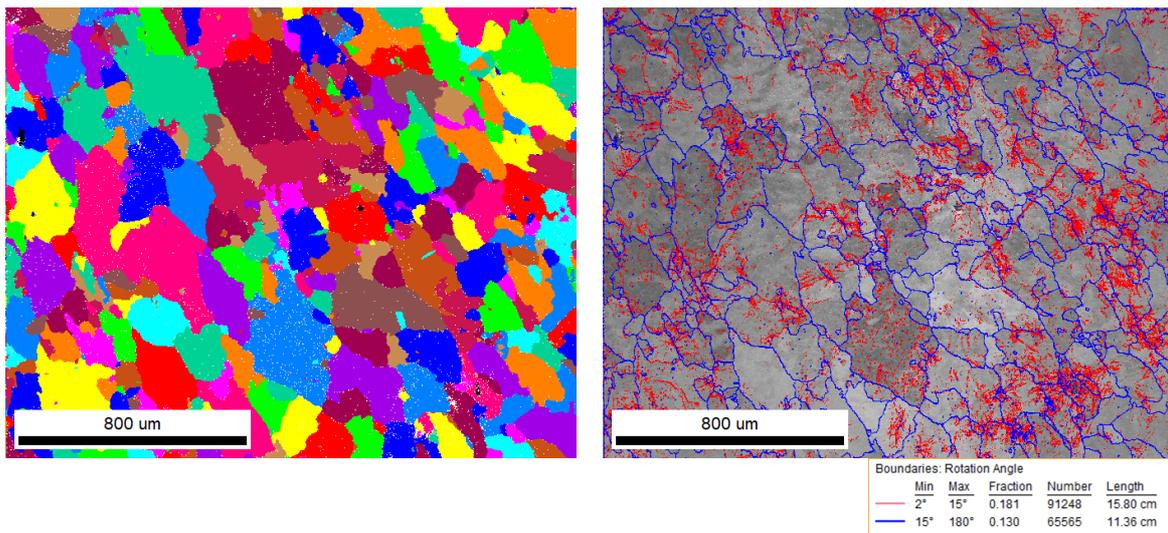| Boundaries: Rotation Angle | | | | |
|---|---|---|---|---|
| | Min | Max | Fraction | Number | Length |
| | 2° | 15° | 0.181 | 91248 | 15.80 cm |
| | 15° | 180° | 0.130 | 65565 | 11.36 cm |

Figure 12: (L) Unique colour coded grain structure and (R) Grain Boundary Overlay on SEM Image with misorientation angle
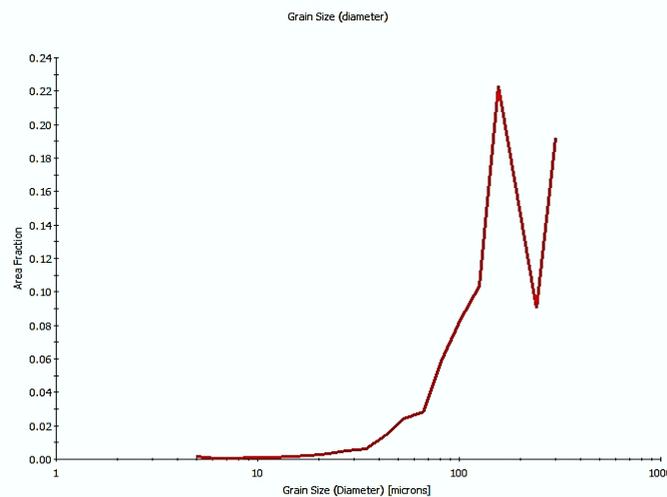
Figure 13: Distribution of grain size

The grain size for aluminum phase ranges from 100 to 300 micron with few smaller grains size observed for other phases and impurities. Both low angle (2°-15°) boundaries and high angle (15°-180°) grain boundaries are observed from the analysis. The ASTM grain number obtaine dis 6.8 which corresponds to "fine grain structure".
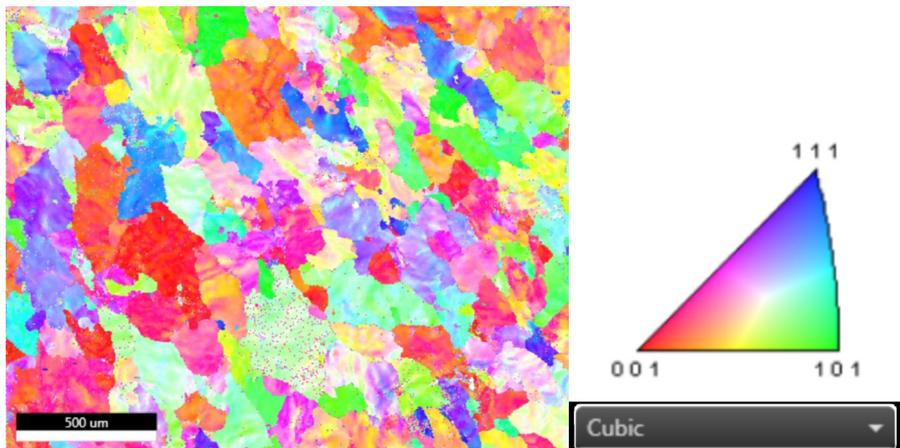
b. Textural Analysis


Figure 14: IPF Mapping of the Sample for Aluminum Phase

c. Phase Analysis

The analysis shows that 98.6% of the sample is composed of aluminum (FCC) structure with Aluminum Manganese and Aluminum Iron Nickel as secondary phases present in the sample. This assessment corresponds with the elemental analysis results obtained.

All these analysis proved that the recovered Aluminium is high quality and could be used for packaging application again and also in other industrial applications. Co product of 3-5% carbon is also valuable and could be used as hard carbon or to generate activated carbons for valuable application.
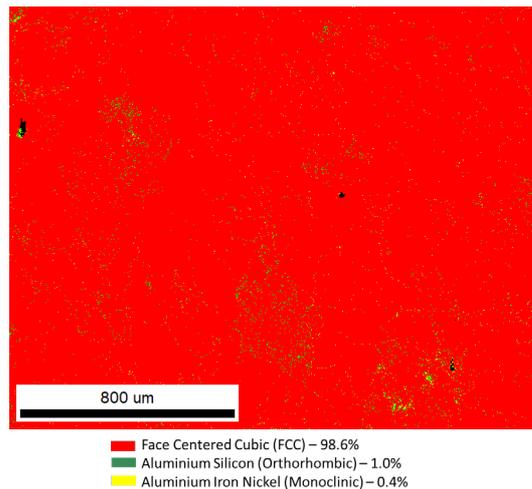
Face Centered Cubic (FCC) – 98.6%
Aluminium Silicon (Orthorhombic) – 1.0%
Aluminium Iron Nickel (Monoclinic) – 0.4%

Figure 15: Compositional Analysis of Different Phases

*Energy Balance*

The primary energy consumption in this study is associated with the thermal processing of MAPW (Multilayered Aluminium Packaging Waste) using a single furnace step at 600 °C for 30 minutes. Inputs such as $CO_2$ and in-house nitrogen gases are excluded due to their negligible and highly variable contribution, depending on operational context.

Table 3 presents the energy consumption for this process at two scales: a laboratory-scale setup treating 100 g of material and a projected large-scale system handling 200 kg per batch. The energy consumption per ton is calculated from both lab-scale and large-scale perspectives. Notably, the lab-scale energy consumption per ton is substantially higher due to the inefficiency of small-batch processing. These values serve as a benchmark for evaluating energy efficiency improvements in future scale-ups.

The estimation of the table can vary depending on the type of furnace/thermal unit, location, and energy source.

The energy consumption per ton for primary aluminium production is significantly higher than for recycling aluminium due to the energy-intensive electrolytic reduction process (Hall-Héroult process) and bauxite refining (Bayer process).

Primary aluminium production: 14,000–17,000 kWh/ton

Recycled aluminium production: ~5–10% of that (~700–1,000 kWh/ton)

In this case, the energy consumption is significantly low, lower than the secondary aluminium production.

Table 3: Energy consumption for thermal processing of MAPW at 600 °C (30 min) by microrecycling technology

| Item | Energy consumption (lab scale – 100 g, kwh) | Energy consumption (200 kg capacity, kwh) | Energy consumption (per ton, kwh) |
|---|---|---|---|
| Furnace at 600 °C (30 min) | 2.07 | 9.39 | 46.89 |

## 5. Community and Stakeholder Engagement

Through collaborative effort with researcher (Dr. Deepika Mathur, Senior researcher, James Cook University, NT) and regional organizations (Centre for Appropriate Technology (CAT), Nhulunbuy Corporation Ltd, and local councils previously involved in waste management programs), access to valuable information and perspectives was obtained. Critical context on logistical, social, and environmental barriers currently confronting by regional communities was unveiled by this organization along with the identification of packaging waste as one of the looming problems. The findings are intended to inform further partnerships with local and Indigenous-led enterprises interested in implementing microrecycling technologies. Through demonstrating a locally adaptable recycling pathway, the study promotes community empowerment through skill development and supports local economic growth within a circular economy framework.

## 6. Conclusion

With aimed to implement circularity in Northern Territory, the present case study investigated the recycling potential of one of the commonly generated packaging wastes i.e. multilayered aluminium packing materials through thermal disengagement technique. As determined during through characterization, experimental aluminum film is laminated on both sides by two different types of polymeric materials. The decomposition of polymer surfaces was done thermal treatment at different temperatures (400°C-650°C) and various treatment periods (10, 20 and 30 min) under argon atmosphere. The optimum condition considering the maximum polymeric decomposition at lower energy consumption was 600°C. Increasing treatment time could facilitate the process of the separation of residual materials from the surface of the aluminum. Different hydrocarbon gases, CO, $CO_2$, $H_2$, $H_2O$, and few other gases were released during experimental process. Those gases carried out huge heat energy which could be utilized for other applications as well as the hydrocarbon gases (especially aromatic hydrocarbons) can be further analysed to reform into high energy $CH_4$

and $H_2$ gases. Aluminum could be easily recycled in both ways by using or not using the inert gas into the furnace chamber. The main difference caused by the atmospheric air is the oxidation of aluminum surface up to 1.5% during the thermal disengagement process though minor oxidation is also unavoidable in case of treatment in inert atmospheric condition. The derived co-product from the decomposition of the polymers was carbon in the range of nano to micrometers in size with a minor trace of oxides of aluminum and silicon. This carbon can be collected for other applications upon further processing.

The demonstrated process provides a replicable and locally adaptable model for remote communities. By combining technology demonstration with active community engagement, it advances the project's overarching aim of delivering scalable, inclusive recycling solutions that support Australia's shift toward a circular economy.

## 7. Recommendations

While existing initiatives including community awareness, reduction of burning at landfill, sale of recyclables, financial incentives to collect waste, container deposit scheme, effective collection through garbage compactor truck and then tipped at a designated spot are the good signs as the initial stage of waste management in NT but many issues still need to be addressed and focused to achieve circularity. Expanding recycling infrastructure, promoting industry-led recycling options, engaging community, increasing financial incentives, creating markets for recycled items and micro-recycling waste are some mentionable actions to be taken into consideration for effective recycling. Apart from that, special emphasis should be given to complex waste for instance, multilayer packaging materials, used batteries, E-waste, tyres etc to incorporate them in circularity loom through efficient and effective ways. Some more recommended issues are as follows-

- Comprehensive data collection approach should be adopted using standardised method which includes electronic data collection, transparent data reporting, data monitoring and rational analysis.
- Recruitment of efficient staff dedicated for waste management chain should also be given consideration for effective waste management.
- Moreover, improving the regulatory framework to address unregulated and unlicensed waste practices should be accomplished.
- Development of recycling infrastructure should be implemented particularly for the wastes which have recycling potential, for instance, PET bottles, cans, battery and mattress.

- Utilization of recycled goods in the placement of virgin materials should be adopted which will mitigate the problems of waste pollution in regional areas.

- Using potential recycling methods available in the current market for various waste particularly for PET bottles, can and mattresses, greener materials (green tiles, 3D printer filaments, building materials, pavement blocks, interior partition) can be developed that foster the uses of resources.

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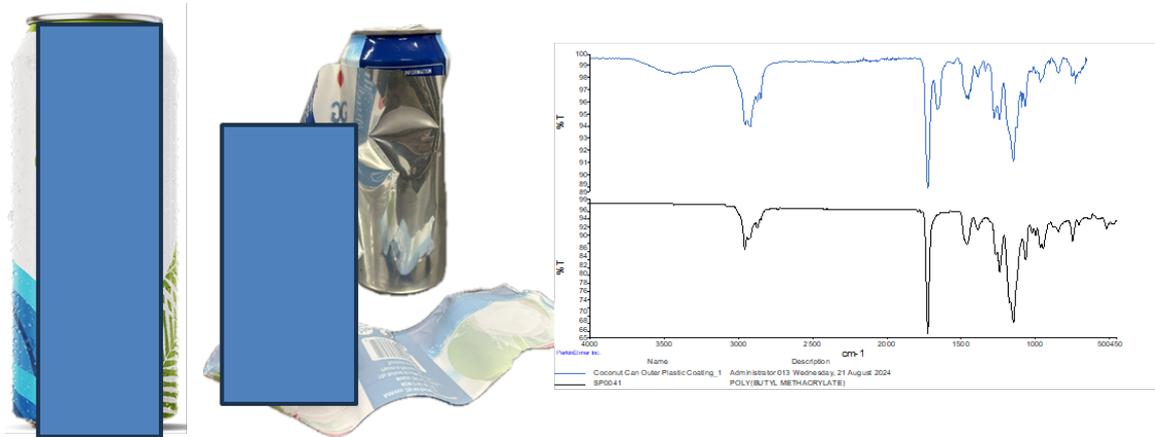
# Supplementary data

## Non-Carbonated Beverage Can:



**Figure1:  Commercial Beverage Can and the**


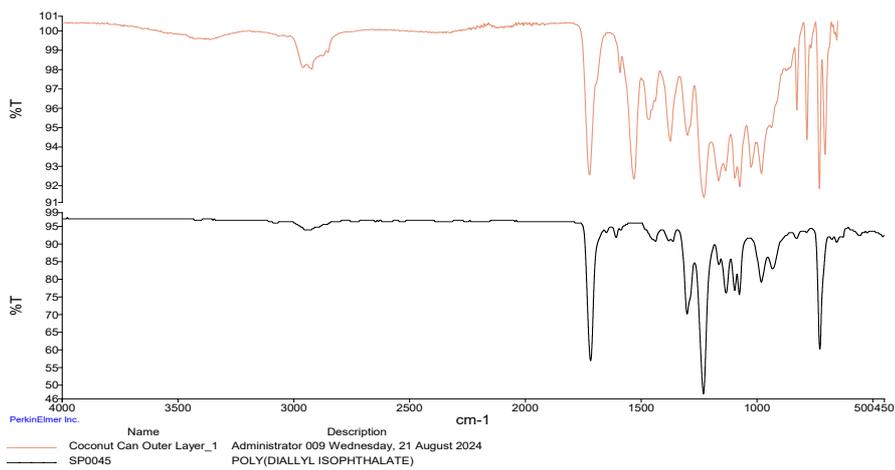
**Figure 1: Outer Layer (Poly butyl Methyl Acrylate)**



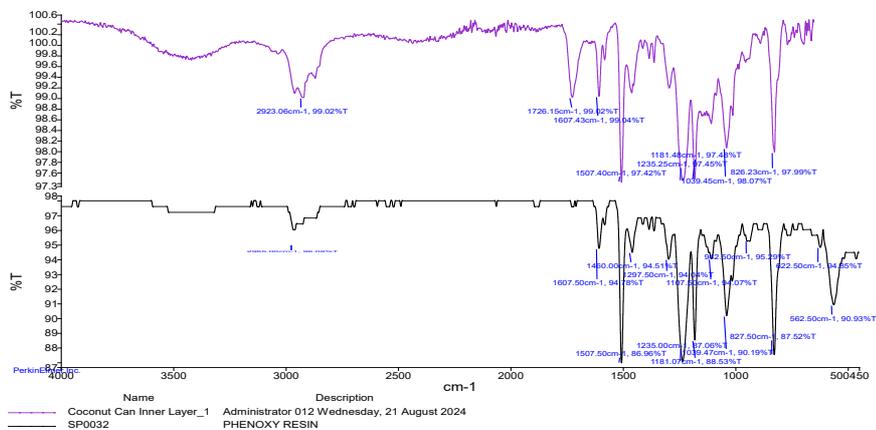**Figure 3: Outer Coating (PBT)**



**Figure 4: Inner Coating (Phenoxy Resin)**

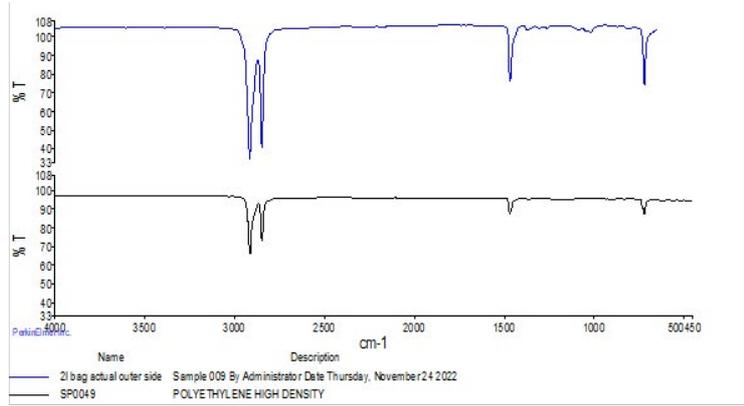## Bag-in-box (BIB) Packaging:



**Figure 5: BIB Packaging**



**Figure 6: HDPE Coating in BIB Packaging**

## Commercial/Industrial Practice:

The following table lists coatings approved for aluminum beverage cans and packaging, compliant with U.S. (21 CFR 175.300) [1], EU (Reg. (EC) No 1935/2004 and Reg. (EU) No 10/2011)[2], and Australian (AS 2070-1999, FSANZ)[3] regulations for food contact safety.

*Table 11: Commercially Used Coatings for Aluminum Beverage Cans and Packaging*

| Coating Type | Applications | Key Properties | Common Epoxies | Common Use Cases |
|---|---|---|---|---|
| Epoxy (BPA based) | Internal (spray) coating, lids and ends | Excellent adhesion, corrosion resistance, flexibility | Bisphenol A based epoxy, BADGE, BFDGE | Legacy use in beer, soft drinks (phasing out gradually) |
| Non-BPA Epoxy | Internal (spray coating), ends | Excellent adhesion, corrosion resistance, flexibility | Epoxy resin with alternative curing agents | Carbonated soft drinks, beer, energy drinks |
| Polyester Resins | External coating and sometimes internal | Corrosion resistance, flexibility, suitable for acidic beverages | Isophthalic/polyester/acrylic-phenolic blends | Juices, teas, soft drinks |
| Phenolic-Based Coatings | Usually for beverage ends | Sulfide stain resistance, corrosion protection | Phenolic resin (phenol-formaldehyde or epoxy phenolic blend) | Limited use in beverage cans and common in food cans |
| Acrylic Resins | Interior coating for acidic products | Heat stability, aesthetic appeal, UV resistance, durable for external printing | Polyacrylate or acrylic-phenolic hybrids or acrylic copolymer (butyl-acrylate) | External surfaces, easy open ends and can bodies |
| Polyolefin Dispersio | External coating | Neutral flavor profile, corrosion | Polyethylene (PE), | Non-carbonated |

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[1] "21 CFR 175.300 -- Resinous and polymeric coatings," in "Electronic Code of Federal Regulations," U.S. Government Publishing Office, 2025-08-04 2025. [Online]. Available: https://www.ecfr.gov/current/title-21/chapter-I/subchapter-B/part-175/subpart-C/section-175.300

[2] "Commission Regulation (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food," in "Official Journal of the European Union," Publications Office of the European Union, 2011-01-14 2011. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2011/10/oj/eng

[3] "Current requirements in the Code for the control of chemical migration from packaging into food in Australia and New Zealand – Proposal P1034," in "Supporting Document 1, Food Standards Australia New Zealand," Food Standards Australia New Zealand, 2015-00-00 2015. [Online]. Available: https://www.foodstandards.gov.au/sites/default/files/food-standards-code/proposals/Documents/P1034-Packaging-CFS-SD1.pdf

| ns | | resistance and high flexibility | Polypropylene (PP), ethylene vinyl acetate (EVA) | beverages |
|---|---|---|---|---|
| Water based coatings | Inner spray coating | Low VOC, retortable, suitable for high temperature process | Water based acrylic polyester or water based non-BPA epoxy | Hit-fill beverages |