REUSABILITY BY DESIGN

SUPPLEMENTARY TECHNICAL GUIDANCE

This document has been researched, written and compiled by:

RECOUP is the UK's leading independent authority and trusted voice on plastics resource efficiency and recycling. As a registered charity, our work is supported by members who share our commitments including a more sustainable use of plastics, increased plastics recycling, improved environmental performance and meeting legislative requirements. We achieve these by leading, advising, challenging, educating and connecting the whole value chain to keep plastics in a circular system that protects the environment, underpinned by evidence and knowledge.

The University of Sheffield is a research university in the Russel Group with a global reputation for excellence in research and teaching. The university is home to over 30,000 students and 7,000 members of staff across a broad range of academic disciplines and specialised research centres including the Advanced Manufacturing Research Centre (AMRC) and the Grantham Centre for Sustainable Futures. Through research, innovation and collaborative working, Sheffield is committed to finding solutions for worldwide social, environmental, and economic challenges.

Pragmatic is revolutionising semiconductor technology with flexible integrated circuits (FlexICs) that make it quick and easy to embed intelligence almost anywhere. Faster to produce than silicon chips, and significantly more cost-effective, FlexICs are thinner than a human hair and, invisibly embedded in objects, enable novel solutions that are simply not possible with conventional electronics.

AMRC Cymru is part of the University of Sheffield Advanced Manufacturing Research Centre and a member of the High-Value Manufacturing (HVM) Catapult, a consortium of leading manufacturing and process research centres backed by Innovate UK. The state-of the-art centre, fully funded with £20m from the Welsh Government and managed by the University of Sheffield, focuses on advanced manufacturing sectors, including aerospace, food and drink and nuclear in the key research areas of future propulsion, sustainability and digital manufacturing.

Packaging samples were kindly provided for testing by Berry Global, Waddington, Sharpak and Faerch and used alongside purchased packaging samples.

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1. Project TRACE

This document has been produced as part of project TRACE (Technology-enabled Reusable Assets for a Circular Economy); a UK Research & Innovation (UKRI) Smart Sustainable Plastic Packaging funded industrial research project lead by Pragmatic Semiconductor Limited. Project TRACE ran from February 2022 to July 2024 and this document has been produced as a result of a work package focussed on reusable packaging design as supplementary technical information to support the 'Reusability by Design' Guidance originally published by RECOUP in 2023.

Project TRACE aimed to address some of the challenges that currently prevent large-scale reuse. Work packages covered the following:

- Understanding consumer perception and how best to encourage adoption
- Developing reusable packaging design guidance
- Enabling item-level traceability throughout the packaging lifecycle
- Ensuring packaging remains safe and fit-for-purpose
- Developing and demonstrating an end-to-end model for collection, sorting and washing infrastructure
- Quantifying the overall environmental impact of moving from single-use to reusable packaging

The core technology innovation is the use of Pragmatic's ultra-low-cost RFID tags to enable a packaging reuse model. These tags provide machine-readable unique codes that allow automated identification and tracking of individual items throughout multiple reuse cycles. Rich data generated can support consumer adoption and infrastructure implementation for optimal environmental impact. For example, the movement of assets within the system, number of cycles, packaging provenance and legislative reporting.

TRACE project partners

Pragmatic

University of Sheffield

RECOUP

AMRC Cymru

KME Ken Mills Engineering Ltd

A Smart Sustainable Plastic Packaging (SSPP) project funded and supported by:

UK Research and Innovation

2. Introduction

The purpose of this document is to provide supplementary technical information to support some of the topics discussed in the RECOUP 'Reusability by Design' guidance[1]. Reusability by Design seeks to provide guidance on areas for consideration for reusable plastic packaging design, taking into account research, industry and consumer views. It aims to highlight the key areas for focus when considering adoption of reusable packaging and the requirements of all areas of the value chain to ensure that appropriate and sustainable choices are made in reusable packaging design and development.

It is noted that continuing work will be required by many parties including designers, manufacturers, academia, service providers, retailers, brands, waste and resource management professionals and governments to address these developing challenges as we accelerate the transition towards a circular economy and the guidance will be updated over time to reflect this.

This document focuses on some of the technical findings as a result of material and sample testing by the University of Sheffield. Samples of materials and packaging for the following polymers were used for testing:

- High Density Polyethylene (HDPE)
- Polypropylene (PP)
- Polyethylene Terephthalate (PET)
- Tritan™
- Polybutylene Terephthalate (PBT)

Practical experience demonstrates that current single-use packaging formats are often suitable for multiple use either with minor adjustments or even without. Realistic numbers of reuse cycles for even well-established reuse systems such as GDB rarely reach more than 25 cycles[2]. One of the aims of practical testing conducted was to explore how different single-use packaging designs will perform through the additional washing steps. Additional aims were to understand how different polymer types and container shapes interact with the washing process, understand the challenges of attaching RFID elements, and the challenges of staining, scratching and allergen risks associated with multi-use to support reusable packaging design.

This report also includes findings from AMRC's demonstrator for the sorting of RFID-enabled reusable packaging as well as end-of-life recyclability findings for RFID technology. Although intended for multiple reuse cycles, reusable packaging will still reach end-of-life at some point, whether this is through factors such as loss from the system or damage.

The intention is that this document can provide practical technical insights for organisations who are designing and using reusable packaging as we continue to scale solutions to reduce the environmental impact of our packaging choices.

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[1] RECOUP | Reuse

[2] https://www.gdb.de/mehrweg/mehrwegsystem/

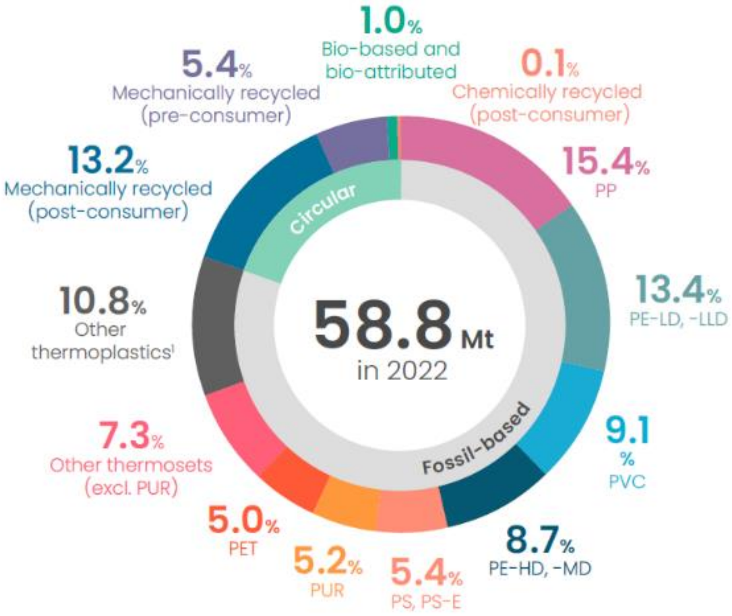
3. Material Testing

3.1 Introduction

Material choice for reusable packaging can be a contentious subject. A shift towards increased uptake of reusable packaging, should be made with the intention to reduce resource consumption and keep materials in the circular economy for longer and thereby reduce environmental impacts. However, some shifts in material choice for reusable packaging have been made to be able to label products as ‘plastic free’, which can appear as greenwashing without evidence that environmental impact has been improved as part of the transition away from plastics. The impact of any material used for reusable packaging should be considered from a life cycle perspective taking into account factors such as total material use, realistic reuse rates and also end-of-life management. By viewing any proposed transition from this holistic standpoint will ensure that the overall aim of reducing environmental impact through the introduction of reusable packaging is prioritised.

Despite plastic having received bad publicity for pollution problems and resource use, these are mismanagement issues rather than material ones. Lightweight and durable, with a range of barrier properties for water, light and oxygen, suitable for use in a range of temperatures from oven to freezer, including microwave, offering versatile visual characteristics, rigid and flexible options, with established reprocessing routes – plastic is an excellent choice for reusable packaging. These properties form a solid foundation for functional packaging that is easy to use throughout the supply chain and helps deliver environmental benefits for the whole reusable packaging system.

European plastic production in 2022, as reported by Plastics Europe[3], was 58.8 Mt, 80.3% of this was fossil-based plastic, 13.2% post-consumer recycled plastics, 5.4% pre-consumer recycled plastics, 1.0% bio-based or bio-attributed plastics and 0.1% chemically recycled plastics. Of this 58.8 Mt the distribution across plastic types is shown in the chart below, 39% of which was attributable to packaging applications.



European plastics production by type

Data Sources: Conversio Market & Strategy GmbH and nova-Institute Sources: Conversio Market & Strategy GmbH, nova-Institute, Polyglobe database by Kunststoff InformationVerlagsgesellschaft mbH, Eurostat (European Statistical Office). The data are rounded estimations. Polymers that are not used in the conversion of plastic parts and products (i.e. for textiles, adhesives, sealants, coatings, etc.) are not included.
1. Includes PBT, PEEK, PEI, POM, PPA, PSU/PES/PPSU, PTFE, PVDF and other thermoplastics not listed separately.

Figure 1. European plastics production by type, Plastics Europe

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[3] Plastics Europe -THE CIRCULAR ECONOMY FOR PLASTICS - A EUROPEAN ANALYSIS | 2024

European plastics converters demand per material type and sector is shown below. For packaging the main polymers used are Polyethylene (High Density (HDPE), Medium Density (MDPE), Low Density (LDPE and Linear Low Density (LLDPE)), Polypropylene and Polyethylene Terephthalate.

Figure 2. European plastics converters demand by application and type

Source: Conversio Market & Strategy GmbH based on the input of the Plastics Europe Market Research Group (PEMRG). The above data are rounded estimations. Demand data are built on estimations of quantities bought by European converters, including imports. Demand for recycled plastics and bio-based/bio-attributed plastics is not included. Polymers that are not used in the conversion of plastic parts and products (i.e. for textiles, adhesives, sealants, coatings, etc.) are not included.

The practical testing for this project focused on five main polymer types:

- High Density Polyethylene (HDPE)
- Polypropylene (PP)
- Polyethylene Terephthalate (PET)
- Tritan™
- Polybutylene Terephthalate (PBT)

A brief overview of each of these polymers' typical applications, characteristics and limitations for use in packaging can be found in Appendix 1.

Polymer choice for reusable packaging is not limited to these five materials. These materials were chosen as they either fit the criteria of commonly used polymers within single-use packaging (Plastics Europe data) in the case of HDPE, PP and PET or have been proven to work in other reuse applications in the case of Tritan™ (a co-polyester produced by Eastman[4]) and PBT (a thermoplastic engineering polymer).

An overview of currently available reuse schemes for cup, bowl and tray formats suggests that the majority of them are manufactured from PP, followed by a small representation of PET, PBT, HDPE and Tritan™. Polymers such as polystyrene (PS), expanded polystyrene (EPS) and poly vinyl chloride (PVC) are the focus of a number of voluntary agreements to be reduced in their applications for packaging, hence this report does not focus on these materials.

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[4] Tritan | Eastman

3.2 Washing Testing – Heat durability and RFID tag adhesion

The results in this section have been provided by the University of Sheffield.

3.2.1 Heat Durability Testing

Introduction

Reusable packaging must undergo repeated washing cycles, undertaken at high water temperatures, to ensure cleanliness and, to some degree, sterility from common pathogens. This work aimed to test a range of lightweight single-use and heavier reusable packaging formats for their heat durability during these washing cycles. The containers were each washed 20 times, as detailed below.

Packaging samples

Packaging samples of different formats and material type were sourced either directly from suppliers or purchased for testing. These were predominantly, but not exclusively, in single-use packaging formats. It was decided to source single-use packaging formats for several reasons; single-use packaging is the target we seek to replace; it is available in a wide range of polymer materials and formats; it is low-cost and widely available. Single-use packaging tends to use a minimal mass of material to minimise costs. It is therefore, likely to have the most optimised environmental impact for a given form and material combination and, thus, a useful minimum standard to test against. If the single-use item is suitable for reuse, the commercial and environmental barriers to its adoption as a reusable container will probably be smaller. This assumption would require verification via an LCA process. There is limited market penetration for Tritan™ and PBT in single-use formats, therefore, samples for these polymers were sourced from the available packaging formats, predominantly reusable containers.

The washing cycle

The commercial dishwashing machine used was a Classeq D500 under-counter washer. This washer is equipped with both upper and lower rotating rise arms. Thus, water jets travel up from below and down from above onto the washed surfaces. The washer uses 500mm x 500mm baskets to hold the washed items. The detergent used was Diversey Suma Nova L6L (active ingredients: tetrasodium (1-hydroxy ethylidene) bisphosphonate and sodium hydroxide, alkaline), and the Rinse Aid was Suma Rinse A5 (glutaral, surfactants). The dosage has been set according to the manufacturer's recommendations. Local water hardness is considered soft (32.2 mg/l calcium, Sheffield, UK (Yorkshire Water, 2024)). The “standard” wash setting was 55°C for the 3-minute wash cycle and 85°C for the 3-minute rinse cycle. Each item underwent 20 wash cycles unless it failed during the wash cycle. A failure was determined if the sample deformed or warped.

Testing arrangement

Due to the low mass of the single-use containers and the force of the washing jets, the lighter containers were placed face down onto the lower washing tray and a metal grid was placed over the containers. This grid was secured by placing a Pyrex dish on the metal grid. The total mass of this arrangement was 2.826 kg. If this was not done, the containers were thrown upwards from the tray and struck the rotating dishwasher arms. In some cases, the cPET containers underwent some minor deformation due to the weight of the Pyrex dish. However, this deformation was slight and was not considered a failure. Large PET bottles were held upright or placed flat on the trays; this would not be the geometry used in a commercial bottle-washing facility. In this case, the bottles would be inverted, and washing solution under pressure would be sprayed up from below to wash the inside and from above and the sides to clean the outside. However, this equipment was not available.

Figure 3. The cPET samples are arranged in the Classeq D500 under-counter washer. The metal grid and Pyrex dish weigh the containers down and prevent them from being flung around the dishwasher. The washing tray is 500mm x 500mm for scale.

Results

Most of the samples (HDPE, PP, cPET, PBT, Tritan™) showed no significant changes during the washing cycles. However, the thin-walled PET samples deformed after five (Figure 4) or nine washes, so the container was removed from further tests. Small wall thicknesses with large unreinforced areas failed during the wash cycle for these PET samples. It should be emphasised that these containers are not designed for reuse and washing at high temperatures. These containers were chosen in advance with the expectation that they would deform on heating as they were thin-walled and had large areas of unsupported thin PET that had been considerably stretched during processing.

The presence of ridges reinforces the wall and reduces warping. Most of these samples showed no distortion after 20 washes; only two containers of this type showed this deformation. PET has a glass transition temperature of 70 °C and a crystallisation temperature of 265 °C, cPET is more thermally stable because it has a higher degree of crystallinity than PET (Mark, 1999[5]). The clear PET bottle has a wall thickness of 0.45 mm, as measured in the centre of the bottle. It also has reinforcing ridges along its length. It did not undergo warping during 20 wash cycles. The clear punnet has a wall thickness of 0.12 mm but has additional reinforcing ridges, but it failed after five washes; another container, with large unreinforced areas and a wall thickness of 0.65 mm, failed after nine washes.

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[5] Mark, James E. 1999. *Polymer Data Handbook*. Oxford University Press.

Therefore, if there are reinforcing ridges, the recommendation would be that the wall thickness should be above 0.5mm. However, these ridges will likely make removing the product more challenging for solids and pastes than for liquids.

Figure 4. Images of wash deformed thin-walled PET punnets

HDPE and PP containers with wall thickness ranging from 0.35 to 0.65 mm performed well in the wash. Insignificant changes in opacity were recorded in PP samples. CPET samples demonstrated suitable stability for the suggested washing conditions, with wall thickness ranging from 0.2 to 0.46 mm. RPET and PET samples of a single-use thickness (0.12-0.85 mm) without strengthening elements such as ridges proved unsuitable for the "standard" washing process due to warping. Any reusable packaging design should be tested to find an optimised wall thickness that is neither too thin nor over-engineered and too thick, which can withstand the washing cycle as well as the other pressures from the reuse system (logistics, return mechanisms, etc.).

3.2.2 Adhesive Tag Testing

Adhesive tag testing was carried out by the University of Sheffield.

Introduction

The purpose of the initial wash testing was to understand more about the durability of NFC (near-field communication) tags within a typical packaging reuse system by using various adhesives to attach the NFC tags to a range of polymer sheets, subjecting them to a commercial washing process and observing any resultant properties and testing functionality. NFC is a branch of High-Frequency RFID.

Polymer sheets

Flat sheets (245 x 245 x 4 mm) of PP and HDPE were sourced and flat sheets of amorphous PET (AxPET)® were cut from large sheets to 300 x 300 x 3.7 mm. Compression moulding polymer pellets created flat sheets of PBT and Tritan™ (165 x 165 x 5 mm). The temperatures and pressure of the moulding process were varied to suit the polymer being processed.

NFC tags/inlays

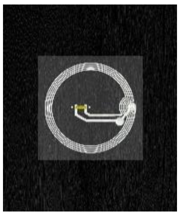

Figure 5. Flexible NFC tag

Typical flexible NFC tag components are PET substrate, an aluminium antenna and a flexible integrated circuit (Figure 5. Flexible NFC tag).

Two types of tag were supplied by Pragmatic for testing. These tags provide machine-readable unique codes that allow automated identification and tracking of individual items throughout multiple reuse cycles. The types of tags supplied were:

- **Type A - Dry inlays with circular NFC antenna**. These tags were cut into a rectangular shape and adhesive applied to attach them to polymer sheets.
- **Type B - Wet labels with circular NFC antenna**. These tags had adhesive already pre-applied and were pre-cut into circular shape.

Adhesives

The following adhesive types were used for each testing phase:

- Washing test 1. Acrylic-based adhesive
- Washing test 2. Rubber-based adhesive
- Washing test 3. Acrylic-based adhesive (food contact approved)

Method

Tags were attached to the flat plate by thumb pressure followed by a soft roller to ensure uniform pressure across the tag. For curved surfaces thumb pressure only was used.

The commercial dishwashing machine used was a Classeq D500 undercounter ware washer. The washer uses 500mm x 500mm baskets. The detergent used was the Diversey Suma Nova L6L and the Rinse Aid was Suma Rinse A5. Local water hardness is considered soft and the dosage was set accordingly to manufacturers recommendations.

The wash temperature setting on the dishwashing machine was 55°C and the rinse temperature was 82°C. The washing duration was set to ‘standard’ with a duration of 3 minutes.

Each sample completed 30 cycles.

Adhesion failure is defined as tag being removed by washing. Minor defects of adhesion were observed and recorded.

The tags were then read by an Android mobile phone (HUAWEI Mate 20 Pro) using the NFC application TagInfo Version 4.25.5 from NXP Semiconductors to determine functionality.

Results

Washing test 1

121 Type A tags with acrylic-based adhesive applied to the back of each tag. These sheets were then stacked vertically in the dishwasher (see Figure 6). Adhesion to the substrate polymer flat sheet was maintained on all tags after 30 wash cycles. The washing removed none of the tags.

Figure 6. Placement of the compression moulded sheets with the type A tags in the commercial dishwasher.

Table 1. Washing cycle durability testing for Type A tags.

Material	PET	PP	HDPE	PBT	TRITAN™
Tile size (mm)	300 x 300	245 x 245	245 x 245	160 x 160	160 x 160
No of Sheets	1	1	1	2	1
Surface area cm2	900	600.25	600.25	256	256
Total area	900	600.25	600.25	512	256
No of tags/sheet	30	29	29	12	9
Total No of tags	30	29	29	24	9
Wash Cycles	30	30	30	30	30

Washing test 2: NFC functionality

138 Type B tags with rubber-based adhesive were tested for NFC functionality before. These tags have a white reinforcing PET backing strip. The sheets were stacked in the dishwasher, but the space between the flat sheets was increased so that the water from the washing jets would be more likely to contact the surface of the sheets directly. The stacking of the sheets was such that the sheets would receive direct spray. The sheets were washed 30 times on the "standard" wash cycle, as detailed on page 9.

All Type B tags remained bonded to the sheets, and no signs of delamination could be observed. The tags were tested for NFC functionality after each wash. A single tag on PBT failed. We do not believe this is due to the PBT substrate and that this tag would have failed on any substrate, as no discernible visual difference could be observed between this tag and the others. It seemed well adhered to the substrate, with no delamination nor signs of water ingress. The tags' 0.7% failure rate requires further investigation over larger numbers to determine an expected value for a large population.

Figure 7. Type B tags on PBT, PP, HDPE and amorphous PET flat sheets. Tags on Tritan sheets were washed separately

Table 2. Washing test 2 results for Type B tags.

Material	PET	PP	HDPE	PBT	TRITAN™
Size (mm)	300 x 300	245 x 245	245 x 245	160 x 160	Container
No off	1	1	1	2	1
Surface area cm2	900	600.25	600.25	256	N/A
Total area	900	600.25	600.25	512	N/A
No of tags/sheet	30	30	30	16	16
Total No of tags	30	30	30	32	16
Tags tested for NFC function before washing?	Yes Functional	Yes Functional	Yes Functional	Yes Functional	Yes Functional
Wash Cycles	30	30	30	30	30
Failures	0	0	0	1 (after 3 cycles)	0

Washing test 3

While we envision the tags being used on the outside of the containers and not in contact with food or drink, we also tested a food-contact-approved acrylic adhesive with the Type A tags. The NFC functionality was tested before washing. The tags were adhered to HDPE, PP, and PET sheets, as well as a Tritan reusable container.

As in washing test 2, the sheets were placed vertically and well-spaced to allow direct impact of the water jets. The Tritan™ container was placed inverted with the tags uppermost (Figure 8). This ensured the tags were immersed in water throughout the washing cycle and received a direct jet impact from above.

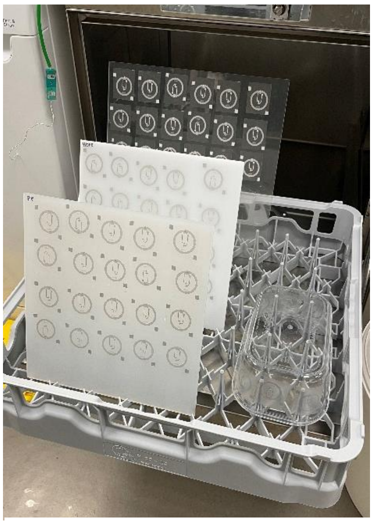

Figure 8. Food contact-approved adhesive on Type A tags. The sheets and Tritan™ container stacked in the dishwasher.

Table 3. Washing testing of Type A tags secured with food contact-approved adhesive

Material	PET	PP	HDPE	TRITAN™
Size (mm)	300 x 300	245 x 245	245 x 245	Container
No off	1	1	1	1
Surface area cm2	900	600.25	600.25	N/A
Total area	900	600.25	600.25	N/A
No of tags/sheet	20	20	20	12
Total No of tags	20	20	20	12
Tags tested for function before washing?	Yes Functional	Yes Functional	Yes Functional	Yes Functional
Wash Cycles	30	30	30	30
No. Of Tags failed to be read	0	0	0	0

Adhesion to the substrate polymer flat sheets and Tritan container was maintained on all tags after 30 wash cycles. The washing removed none of the tags.

All the tags tested passed the NFC functionality test after 30 washes.

Results summary

Washing tests confirmed the durability of the NFC tag application using supplied adhesives. Adhesion was maintained on all tags after 30 wash cycles. Five types of polymers were tested, and no differences in adhesion between different polymers were identified. 229 working tags were tested for functionality, and only 1 tag failure was recorded (failure after the cycle 3 out of 30).

Additional comments:

Some of the Type A tags had a metallised guiding marker on the corner where peeling was observed. This metallised guiding marker is not a functional part of the tag and is not present in the final tag application. The corner's rectangular shape means that it has a larger edge profile, making it more likely for water to get under it. The aluminium in the metallised square at the corner creates a difference in thermal expansion. As the sample is thermally cycled over the washing cycle, this difference in thermal expansion creates thermal stress in the film and adhesive layer, resulting in delamination. The recommendation was to avoid metalized elements near the edges of the tag.

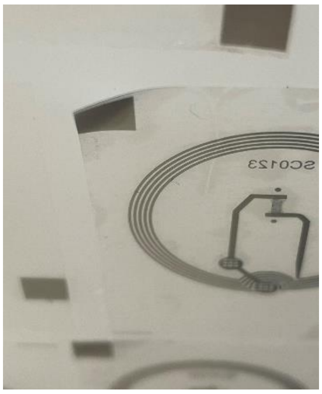

Figure 9. Rectangular tag peeling on metallised guiding mark corner.

3.2.3 Tags on Curved Surfaces

The flat sheet testing showed that the circular reinforced tags (Type B) resisted delamination. The next test was on cylindrical containers with curvature in one direction, domes and bottles with curvature in two dimensions, and uneven surfaces, primarily bottle ends and weld lines. The limited flexibility in the circular Type B tags allowed the tags to bond well to surfaces curved in one

Figure 10. Tags adhered well to containers with curvature in one

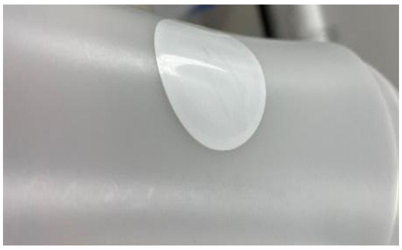

Figure 11. Sample with curvature in two directions. Showing good tag adhesion.

Figure 12. Samples with low radii of curvature in two dimensions showed the expected wrinkling due to the limited flexibility of the tag.

Figure 13. Wrinkling is present when the tag is applied to the base of a bottle

dimension (Figure 10). The tags also bonded well to surfaces with curvature in two dimensions as long as one dimension has a high radius of curvature (Figure 11). As expected, domed samples with small radii of curvature created wrinkles in the tags (Figure 12) and samples applied along welding lines also showed wrinkling (Figure 13). Samples with pronounced wrinkles from the edges would provide spaces for food and contamination to collect when in use and, thus, are unsuitable locations for tag placement. However, they were still tested in the washing cycle.

The Type A tags with the food-contact-approved adhesive and the reinforced circular tags were tested. The containers were washed for 20 cycles with the “standard” wash cycle.

All tags were tested for readability and 100% passed. No tags were completely delaminated, and all maintained good adhesion to surfaces despite observed wrinkling in some cases.

3.2.4 Recommendations

Based on the test results, applying NFC tags to plastic reusable packaging using adhesives proved viable. Adhesion and tag functionality were maintained during 30 washing cycles. Rubber-based, acrylic-based, and food-contact adhesives provided sufficient adhesion to all five polymer types tested.

Application of the tags to uneven, curved or irregular surfaces should be avoided unless absolutely necessary. While functionality and adhesion on these surfaces were maintained, preliminary film failure can be expected due to wrinkling and blisters.

3.3 Peanut Allergen Testing

Peanut allergen testing was carried out by the University of Sheffield.

3.3.1 Introduction

Hygiene concerns, including the risk of allergen contamination, are one of the leading barriers to the adoption of reusable packaging expressed by both consumers and retailers. The following tests were performed to identify if allergen transfer risks rose due to the packaging being used multiple times and scratched during use cycles. Multiple-use cycles can subject plastic surfaces to interaction with hard objects during filling, consumption and washing. The areas of minor surface damage can potentially collect and retain contaminations such as allergy agents. These tests were conducted to understand if risks increase as number of reuse cycles rise.

3.3.2 Methodology

ELISA (enzyme-linked immunosorbent assay) tests were conducted to determine the risk of allergen contamination on scratched plastic surfaces after washing in the commercial dishwasher. A calibration was performed with known solution concentrations as detailed in the ELISA test instructions. The ELISA test has a limit of detection limit of 6.7 ng/ml (ppb). For full protocol instructions and details of the analysis, see the manufacturer’s product details E96PNT: 3M Product Instructions: Enzyme-Linked Immunosorbent Assay (ELISA) for Quantitative Analysis of Peanut Proteins)[6].

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[6] 3m-peanut-protein-elisa-kit.pdf (neogen.com)

Polymer flat sheets of HPDE, PP, PET and Tritan™ were scratched in a cross-hatch pattern by hand (Figure 14)

A ceramic dinner plate was also tested as a control. All sheets and the plate were coated with a thick (>3mm) layer of peanut butter. All sheets were washed on the standard wash cycle (see page 9) in the commercial dishwasher. Sheets were removed and swabbed across the surface forwards and backwards, then rotated 90° and swabbed again. Care was taken to access the scratches as much as possible. The swabs were placed into vials and sealed. The ELISA tests were undertaken in the biochemistry lab as specified in the test instructions. The solutions were examined by a fluorescent probe plate reader. A calibration was performed with known solution concentrations.

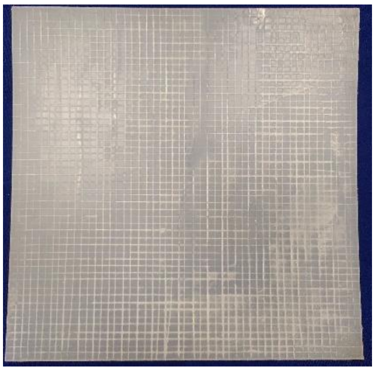

Figure 14. An example of one is the scratched plastic plates. For scale, the edge length is 300mm.

3.3.3 Results

The last column in the tables below demonstrates the measured concentration of the allergy-inducing agent, and it is significantly lower than the analytical limit of detection (6.7 ng/ml). There is an insignificant variation between polymers, and readings for the scratched plastic plates are slightly elevated compared to ceramic plates (0.0781 ng/ml). However, all readings are significantly below the threshold for initiating an allergic response, indicating that industrial washing of reusable containers can help mitigate allergy risks.

Table 4. PP, PET and HDPE scratched plates results

Sample	Test No.	Material	Absorbance (450nm)	Average	ng/ml
1	1.1	PP	1.20	1.87	0.0928
2	1.1	PET	1.93		0.1059
3	1.1	HDPE	1.12		0.0914
4	1.2	PP	1.94		0.1061
5	1.2	PET	2.05		0.1081
6	1.2	HDPE	4.29		0.1479
7	1.3	PP	0.93		0.0880
8	1.3	PET	1.47		0.0976
9	1.3	HDPE	1.90		0.1054
10	2.1	PP	1.74	2.66	0.1024
11	2.1	PET	4.95		0.1596
12	2.1	HDPE	4.82		0.1574
13	2.2	PP	1.80		0.1035
14	2.2	PET	3.45		0.1330
15	2.2	HDPE	1.70		0.1018

16	2.3	PP	2.95		0.1241
17	2.3	PET	0.99		0.0892
18	2.3	HDPE	1.50		0.0982

Minimum Performance Characteristics
The analytical Limit of Detection (LOD) is 6.7ng/mL (ppb)
Clinical response minimum 100mg (100 microgram)

Table 5. Tank water and reference porcelain plate results.

Test sample	Absorbance (450nm)	Concentration ng/ml
Prewash tank water	0.51	0.0806
Water tank after 3 washes and tank drain	0.65	0.0831
Water tank after 3 washes between tests	0.61	0.0824
Clean / Unused samples after tank swab	0.48	0.0801
Porcelain Plate	0.37	0.0781

All results were below the approved detection limit of the ELISA test. A further calibration was undertaken at lower concentrations. While this is not in line with the ELISA kit manufacturer's instructions, this was undertaken to allow an estimate of the differences with the control ceramic plate to be established. Scratched sheets after washing in the commercial dishwasher show more peanut residue than the ceramic dinner plate, up to a factor of two. However, all samples are considerably below what is required to elicit an allergic reaction. (Sampson 1990[7]; Jonathan O'B. Hourihane et al. 1997[8]; J. O. Hourihane et al. 1997[9]).

3.3.4 Conclusions

All polymer samples show a very low concentration of residual peanut after washing. All levels detected were below the approved detection limit of the test and well below that reported to elicit an allergic response.

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[7] Sampson, Hugh A. 1990. 'Peanut Anaphylaxis'. *Journal of Allergy and Clinical Immunology*, Forty-seventh Annual Meeting, 86 (1): 1–3. https://doi.org/10.1016/S0091-6749(05)80115-0.

[8] Hourihane, J. O., S. J. Bedwani, T. P. Dean, and J. O. Warner. 1997. 'Randomised, Double Blind, Crossover Challenge Study of Allergenicity of Peanut Oils in Subjects Allergic to Peanuts'. *BMJ (Clinical Research Ed.)* 314 (7087): 1084–88. https://doi.org/10.1136/bmj.314.7087.1084.

[9] Hourihane, Jonathan O'B., Sally A. Kilburn, Julie A. Nordlee, Susan L. Hefle, Steve L. Taylor, and John O. Warner. 1997. 'An Evaluation of the Sensitivity of Subjects with Peanut Allergy to Very Low Doses of Peanut Protein: A Randomized, Double-Blind, Placebo-Controlled Food Challenge Study'. *Journal of Allergy and Clinical Immunology* 100 (5): 596–600. https://doi.org/10.1016/S0091-6749(97)70161-1.

3.4 Reconditioning

Reconditioning testing was carried out by the University of Sheffield.

3.4.1 Introduction

Some packs will not incur internal scratches due to functionality and design e.g., beverage containers. However, scratches will incur from wear whilst from moving through the reuse process. Scratching will occur in the refilling and handling processes as the equipment tends to have stainless steel guide rails. Some facilities have PTFE (Polytetrafluoroethylene) guide rails, which will minimise scratching. It is well established that harder materials scratch softer ones, but the appearance of scratches is what we are seeking to avoid. Light colours tend to show less visibly contrasting scratches for a similar scratching force. Testing completed for the Many Happy Returns Project (NERC Grant Ref: NE/V010638/1).

3.4.2 Bowl Reconditioning Study

Scratching has been noted as a problem in terms of customer and retailer acceptance of reuse items. We undertook test to recondition the bowls and reduce the appearance of scratching.

Scratching process

Scratches were created by two methods:

Method 1: Hand scratching with a serrated metal knife. This results in a small number of deep scratches.

Method 2: Rotating wire brush with digital scale. This results in many lighter scratches at lower forces. Prolonged use results in deeper scratches. This method produces large amounts of microplastics and therefore careful cleanup is required after use.

Reconditioning process

All samples were rinsed with water to remove residual plastic particles and then heat treated.

Heat Treatment 1: A hand-operated heat gun was used to heat the surface. The high temperature but low thermal capacity of the air results in rapid healing of the scratches but does not transfer a large amount of heat to the polymer container. Therefore, only the edges of the scratches contract and shrink. The scratch surface flattens out, and the repair is rapid and localised. This method and variations on it are commonly used to recondition plastic items, for example, stadium seats are “flamed” to return their glossy appearance[10]. While this method could be automated, it was felt that it would be challenging and require the integration of a machine vision system and robotic control of the heat gun's position and speed of movement.

Heat Treatment 2: To assist in the automation of the mould repair, a heated mould system was created. This system consisted of a heated mould that replicated the internal surface of the mould. The test was to place the scratched item onto the hot mould, rotate the item by 20-30 degrees, and remove it.

This did not prove successful, as the item invariably became stuck to the mould. To solve this problem, the heat must be rapidly removed from the mould. This could possibly be accomplished

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[10] https://www.youtube.com/watch?v=NjDbttpJ3GY

with the use of high-power Peltier heat pumps. However, the cost and complexity of this were not justifiable with the available resources.

3.4.3 Conclusions

Our recommendation would be to use the heat gun and a manual process in order to recondition scratched containers.

3.5 Staining Testing

Staining testing was carried out by the University of Sheffield.

3.5.1 Introduction

Staining of reusable packaging can be a critical factor affecting consumer adoption and perception of cleanliness. Food colouring agents can stain reusable packaging during filling and use stages. These tests were performed to understand the reaction of the most common polymers to the most common staining agents.

3.5.2 Methodology

Staining solutions:

- Turmeric in water,
- Turmeric in sunflower oil,
- Paprika in sunflower oil,
- Tomato puree
- Blackcurrant jam

Temperatures:

1) 20°C for 28 days - standard, room temperature test
2) 50°C for 9 days - “accelerated” test

Test protocol based on:

- ASTM D570-22, “Standard Test Method for Water Absorption of Plastics”
- ASTM D1712-09(2020), “Standard Practice for Resistance of Plastics to Sulphide Staining.”

Samples’ dimensions:

- Approx. 40-60 mm x 25 mm

Samples’ materials:

- Unpigmented HDPE, PP, PET, Tritan™, and two pigmented cPET (green, reddish-brown).

The prepared solutions were poured into glass Coplin jars, which are commonly used to stain samples for microscope analysis. The jars have vertical ridges that allow five samples to be immersed in solution, keeping the samples separate from each other and allowing the solution to infiltrate from both sides of the thin sheet.

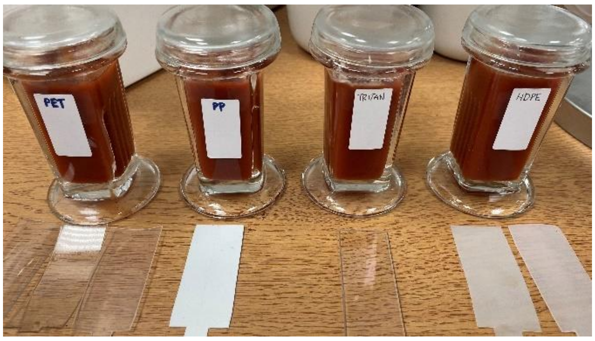


Figure 15. Coplin jars with tomato puree for immersion tests.

For the accelerated test, these jars were placed in a 50 °C water bath with the water level just below the neck of the jar. For the room-temperature test, samples were stored on the lab bench.

The colour of each sample was determined by a colourimeter (PCE Instruments, RGB2). This was adapted to improve the reading stability by excluding ambient light. The samples were placed on a piece of white card with sagittal markings to align the sample and the colourimeter so that data was collected from the same area. RGB (red, blue, green) values were taken from the colourimeter, and the differences between the initial and final RGB values are shown in the results section.

3.5.3 Results

The accelerated 50 °C samples were expected to show more pronounced changes than the room-temperature samples; more importantly, the changes would be in the same direction. However, the tests that were conducted didn't meet these expectations and the "accelerated" test findings were therefore not included in the results. It is recommended that different testing methodologies be

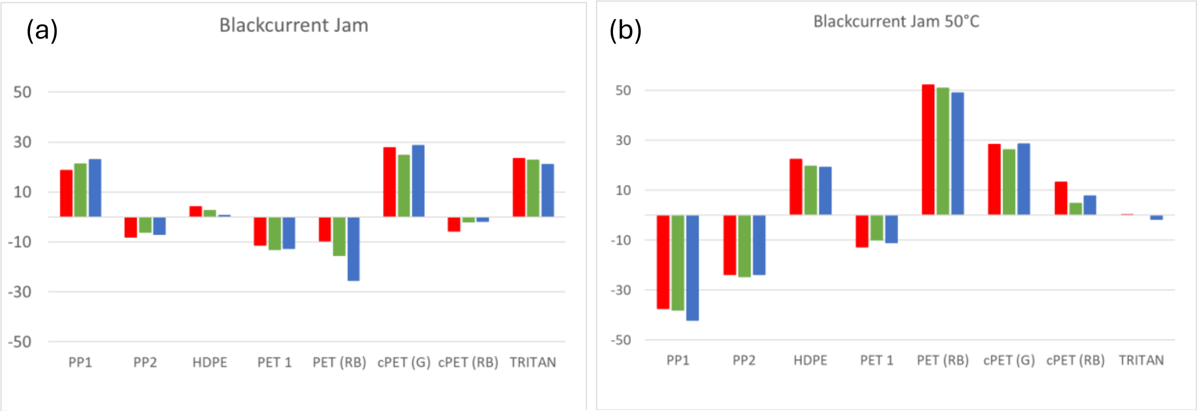


Figure 16. Colourimeter RGB channel differences for blackcurrant solution at (a) room temperature and (b) 50 °C. X axis – polymer types, Y axis - colorimeter RGB channel reading differences between pre-staining and after-staining values.

developed if the relationship between material, staining agent and raised temperature needs to be determined.

At room temperature, paprika pigment in sunflower oil caused the most changes in reading in all polymers, followed by turmeric solutions and tomato puree, with the blackcurrant staining agent causing the most minor changes.

The HDPE sample demonstrated the highest reading change in response to exposure to paprika and tomato agents and minimal reactions to turmeric and blackcurrant.

Pigmented CPET samples showed the lowest measurement variation between pre and after-staining for all staining agents.

Tritan™ demonstrated the highest change in measurements in response to turmeric in water solution.

Long-term tests of pigmented systems.

Samples of the pigmented PET and cPET were immersed in blackcurrant solution (undiluted Ribena®) and turmeric in oil for periods of 83-88 days at room temperature. These were chosen, as the other solutions developed fungal growth on the surface between one week and three weeks. Results: Samples didn't show a change in colour detectable by eye. cPET sample with the red-brown pigment is the most resistant to staining. There is a difference between colour absorption by the matt and gloss surfaces of the container. However, the difference is negligible from the visual point of view.

Observation:

The results demonstrated that staining is less apparent when darker materials are used.

4. Reader and Tag Positions on Sortation System

The information in this section has been written by AMRC Cymru based on a sorting demonstrator constructed for the TRACE project.

4.1 Introduction

The purpose of the automated sortation system is to sort packaging into separate bins based on their material or type by reading the unique codes of RFID tags and comparing them to a database. To avoid missing or misreading tags, maximum RFID reader coverage of the area in which the tags are read must be ensured. The proximity and orientation of a RFID tag relative to the reader is paramount for successful communication. The ability of any RFID reader to energise and communicate with the tag diminishes rapidly with distance. Moreover, the orientation (e.g., parallel vs. perpendicular alignment) affects the electromagnetic field's effectiveness in powering the tag and facilitating data exchange. Ensuring optimal positioning can significantly enhance the reliability of interactions.

When an NFC tag is aligned in parallel proximity to the reader, the electromagnetic field generated by the reader optimally intersects with the tag's antenna, maximizing energy transfer and data exchange efficiency. This orientation fosters a read volume that is maximally extended to facilitate reliable communication. Conversely, as the tag deviates from this parallel alignment, the read volume experiences a consequential distortion or displacement. Such changes manifest as reductions in read range, shifts in the read location, or even the creation of spatial zones where communication is intermittently successful or altogether fails.

In the process of identifying the most advantageous positioning for each reader within the sorting line, a series of preliminary investigations were undertaken during the SORT-IT project, the precursor to TRACE. These exploratory studies used silicone chipped Bullseye tags in conjunction with the DISCO RFID reader to ascertain the feasibility and efficiency of various configurations.

Despite the transition to the Pragmatic manufactured tags and new ST25R3911B-DISCO RFID reader combination in the subsequent TRACE project, it is appropriate to note that the antenna shape/dimensions for both the tag and the reader remain relatively consistent. Consequently, the fundamental principles of physics governing the interaction between the tag and reader suggest that the configurations delineated based on read volume shapes from the SORT-IT project retain their relevance and applicability. This was the foundation for optimising reader positioning in TRACE, notwithstanding the change in hardware specifications.

4.2 Read Volume

Read volume refers to the 3-dimensional space, or volume, around a reader where a tag can be detected and successfully read. This 3-dimensional space’s shape and size can change depending on factors like the angle of the tag against the reader. The goal of understanding and mapping this space is to understand how well the reader can detect tags in different positions and orientations.

Objective

To map out the read volume of the tag by systematically varying its distance and lateral position relative to the reader, and to compare the effects of the tag's orientation (parallel vs. perpendicular) to the reader on its detectability.

Methodology

Setup: Two sets of experiments were conducted using the same reader and identical tags. In the first set, the tag was oriented parallel to the reader's surface. In the second set, the tag's orientation was perpendicular to the reader's surface.

Procedure

- The reader was fixed in a stable position on a non-metallic surface to avoid interference.
- Starting at a zero distance (direct contact), the tag was gradually moved away from the reader in 10 mm increments, noting the maximum distance at which the reader successfully detects the tag.
- Subsequently, the tag was moved laterally away from the reader's central axis in 10 mm increments, up to the point where the tag was no longer detectable.
- Each measurement was recorded, with separate tracks for the parallel and perpendicular orientations.

Data Collection

The experiment recorded the maximum read distance (in mm) for both orientations at each lateral position, creating a dataset to analyse the read volume shape and extent.

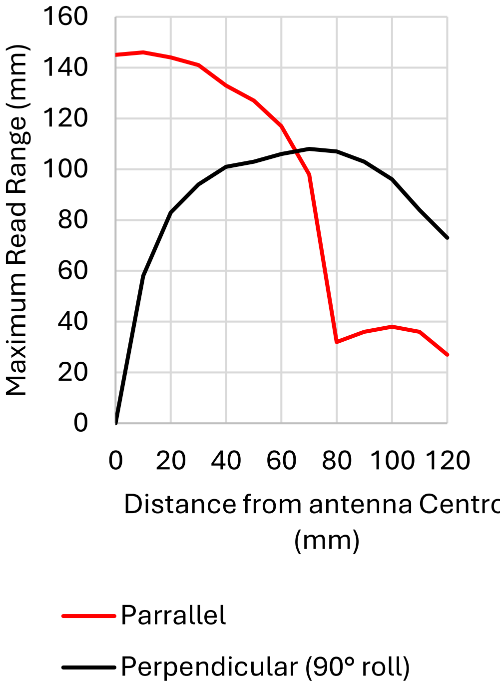


Figure 17. Read vol. of Bullseye tag with ST25R3916 reader

The graphed data aligns with anticipated patterns regarding the orientation of the reader and tag, illustrating how the read volume undergoes distortion and displacement when the tag is positioned perpendicularly. Notably, the maximum read distance is observed to shift laterally by approximately 70 mm from the reader's central axis. This orientation results in a notable spatial gap directly above the reader's centre, evidencing the significant impact that perpendicular tag orientation has on the distribution and effectiveness of the read volume.

4.3 Recommended Reader Positioning

The read volume data was duplicated to simulate the presence of multiple readers, with their respective read volumes superimposed and adjusted strategically. An example of the static read volume for a tag placed perpendicular to 6 readers orientated below and to the sides is presented in Figure 18.

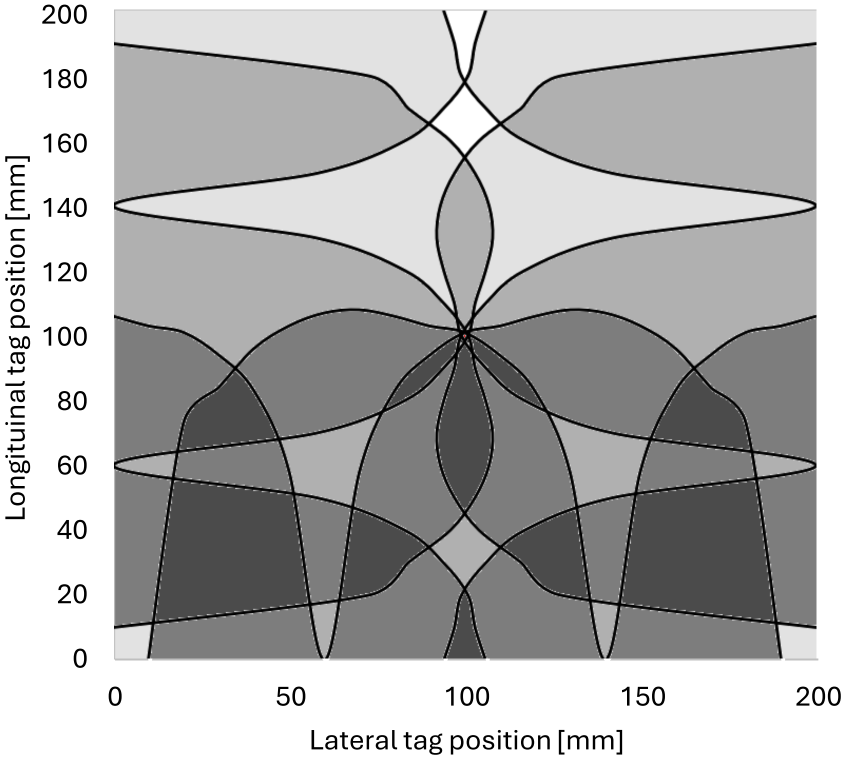


Figure 18. Superimposed read volume with tag in 90° pitch position

Reader Placement

Employing this methodology, an optimal strategy was determined by arranging an array of six readers within a designated segment of the conveyor line, as depicted in Figure 19. Readers 1 and 2 were positioned beneath the conveyor, oriented upwards, whereas readers 3 through 6 were mounted on the sides at a 90° angle to ensure lateral coverage. This configuration ensures coverage over the entire conveyor area, accommodating all possible tag positions and orientations. Furthermore, the readers were staggered in pairs, enhancing the coverage by ensuring that each individual surface area was thoroughly scanned.

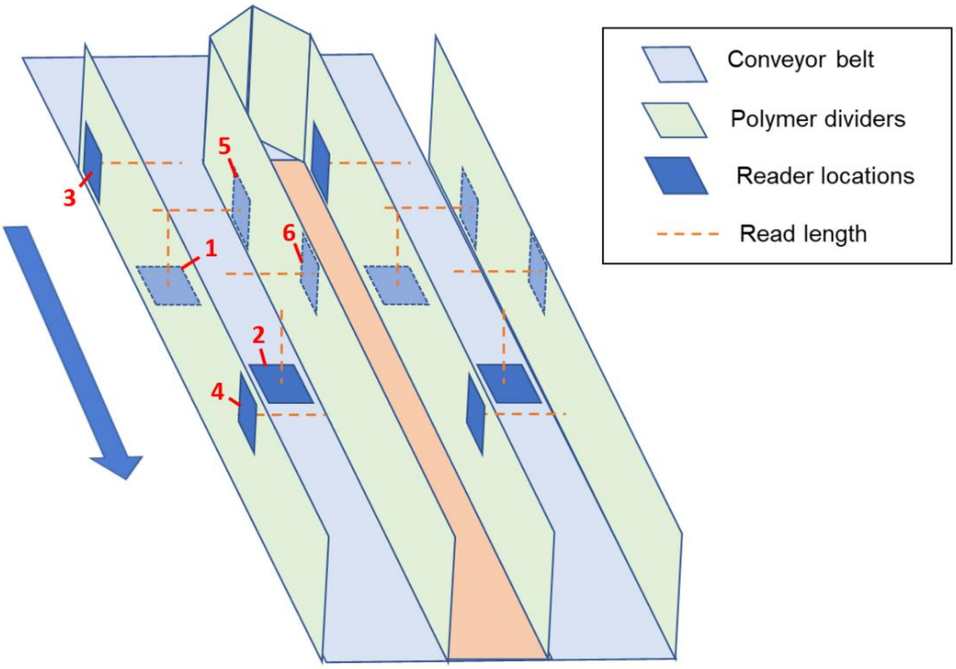


Figure 19. Optimal reader configuration/coverage

Read Frequency

Upon establishing optimal positions of the readers to encompass the sortation conveyor's cross-sectional area, the longitudinal aspect, or z-axis, of the read volume was analysed. This analysis, in conjunction with factors such as read time and the conveyor's velocity, was mathematically modelled. The purpose of this modelling was to ascertain the frequency with which a tag could be read at any specific location along the conveyor.

Assumptions Incorporated into the Model:

- Read Volume Adjustment: An intentional diminution of the read volume at its peripheries was assumed, aiming to enhance the likelihood of tag activation. This adjustment accounts for the decreased probability of tag energization at the outer limits of the read volume.
- Impact of Reader Placement: The model considers a decrease in read volume attributable to the spatial separation of the reader, necessitated by the placement of electronic components. This separation affects the reader's efficacy in energizing the tags.
- Read Time Specification: The model presumes a read time of 50 milliseconds, a critical parameter in determining the interaction window between the tag and reader.
- Conveyor Speed: A constant conveyor speed of 1 meter per second is assumed, providing a baseline for calculating the potential read instances within the system's operational dynamics.

This modelling approach facilitates an understanding of the system's capability to reliably detect tags, considering the intricate interplay between physical positioning, technological limitations, and operational parameters. The results of the spatial frequency distribution against tag orientation are presented in Figure 20.

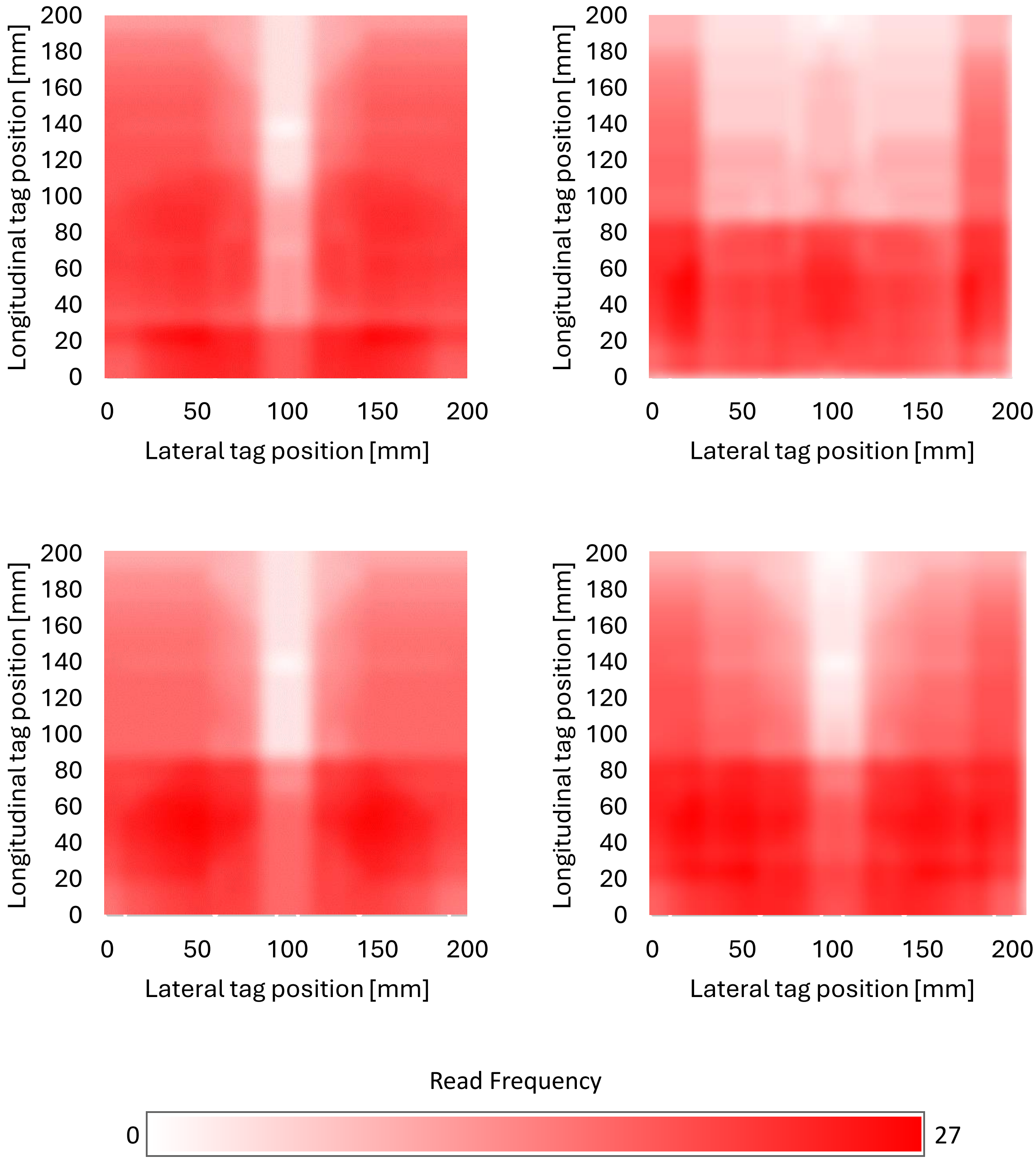


Figure 20. Read frequency based on tag position (a) Parallel to conveyor (b) Perpendicular 90° roll to conveyor direction (c) Perpendicular 90° pitch to conveyor direction (d) Averaged result

Examining the graphical representations, it becomes evident, perhaps somewhat intuitively, that there is a heightened frequency of tag reads in closer proximity to the readers. Moreover, in scenarios where multiple readers are deployed. A discernible limitation on the read range capacity becomes apparent, particularly in the central and upper regions of the coverage area. The read range capacity may be somewhat restricted in the upper regions, as shown by the low frequencies in the centre of the lateral tag position and the upper half of the longitudinal tag position displayed in Figure 20.

4.4 Recommended Tag Position on Item

The shift in read volume observed when scanning tags at an angle has revealed a possible positional inaccuracy of up to 70 mm. This degree of inaccuracy, when factored into the calibration of air jet operations for sortation purposes, can significantly impact the system's effectiveness. Specifically, when tags are affixed at one extremity of an item, this possible 70 mm discrepancy may result in a sortation error, which may cause the air jet to miss its target. To overcome this possible risk, it is advisable to position tags centrally on the packaging, thereby maximising the likelihood that the air jet accurately impacts the item.

Additionally, strategic placement of tags on parts of the packaging that are predisposed to orient towards lower and outer positions during sortation can further enhance the system's reliability. This practice ensures that tags remain within the optimal read volume, thereby reducing the chances of sortation failures and improving overall system efficiency.

5. Recyclability of Plastic Packaging with RFID Tags

The information in this section is based on a research study carried out by Ahamed et al, 2024[11] to support the TRACE project.

While the benefits of the inclusion of RFID tags to reusable plastic packaging have been widely accepted, there has been limited focus on the impact of RFID tags on the recycling of plastic packaging materials. There are two possibilities for the recycling of RFID tags:

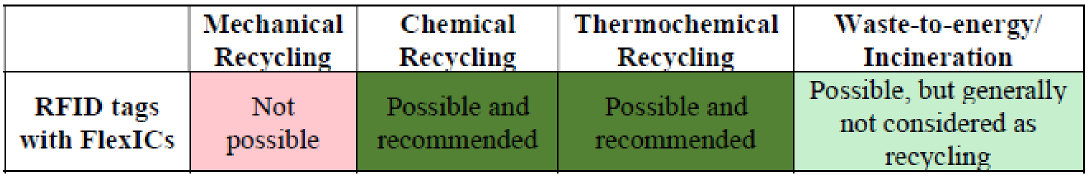
1. Recycling as a separate entity after segregation from the plastic packaging
2. Recycling along with the plastic packaging

5.1 Recycling RFID tags (as a separate entity)

RFID tags can be recycled as a separate entity where they can be separated from the packaging before entering the recycling process. Tags adhered to the packaging can be detached via a number of pre-treatment methods such as UV irradiation, caustic washing or heat treatment. Caustic washing as a process is currently commonly used in mechanical recycling facilities.

Potential end-of-life treatment options for RFID tags are shown in the table below. Among the predominantly available recycling technologies, including mechanical, chemical, and thermochemical methods, chemical recycling appears to be the most promising and has the potential to retain the maximum value of the RFID tag components. Mechanical recycling of tags is not feasible as electronic tags contain several components, including the substrate, antenna, and IC chip. Conversely, the application of thermochemical methods would produce pyrolysis oil or syngas and metals as products. In the case of energy from waste, the energy resulting from the combustion of the tag material is recovered, while the metals remain as residues of combustion.

Table 6. Potential end-of-life treatment options for RFID tags



	Mechanical Recycling	Chemical Recycling	Thermochemical Recycling	Waste-to-energy/ Incineration
RFID tags with FlexICs	Not possible	Possible and recommended	Possible and recommended	Possible, but generally not considered as recycling

As a proof of concept, chemical depolymerisation of RFID tags (Figure 1) was carried out in collaboration with the University of Manchester. A solvent (Ethylene Glycol) and organocatalyst were used to depolymerise the RFID tags at elevated temperature (140 °C) until completely dissolved. The products of depolymerisation were BHET (Bis-(2-hydroxyethyl) terephthalate – a precursor to PET) and metals (from the antenna and IC).

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[11] Technical and environmental assessment of end-of-life scenarios for plastic packaging with electronic tags - ScienceDirect

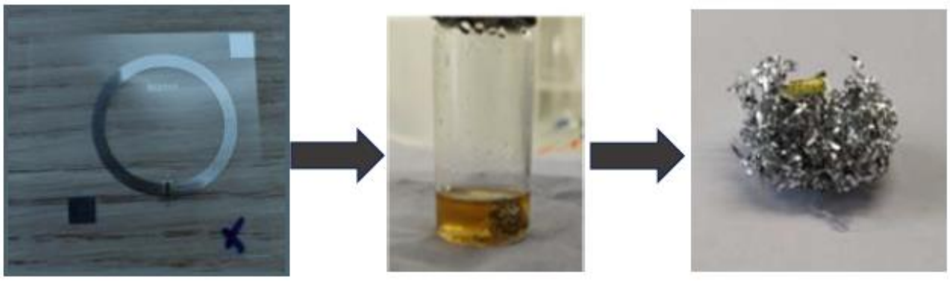

Figure 21. Chemical depolymerisation of RFID tags.

5.2 Recycling Plastic Packaging with RFID Tags

In this scenario, the recyclability of tags along with plastic packaging is taken into consideration. Possible end-of-life treatment options for RFID tags along with the different types of plastic packaging include both mechanical and chemical recycling routes.

Experimental investigation including mechanical recycling and chemical depolymerisation were conducted for a use case of PET bottles with RFID tags. This is detailed in the next section of the report.

5.3 Recycling Trials

Pragmatic and The University of Manchester carried out trials looking at the mechanical and chemical recyclability of PET pellets and bottle flakes combined with an RFID tag comprised of PET substrate, an aluminium antenna, a flexible integrated circuit, epoxy paste and an acrylic-based transfer adhesive.

Mechanical recycling

Recycled PET pellets and RFID tags (cut into 2mm squares) were mixed at a weight ratio of 20:1 and then extruded and granulated. The same tests were also carried out on virgin PET and recycled PET without the addition of RFID tags as a control.

Thermal and spectroscopic analysis of the virgin, recycled pellets and recycled pellets with RFID was carried out. The results showed similar chemical structural signatures across all samples suggesting that the small relative mass of the tag components is dominated by the plastic resin signals.

While the material chemistry was largely unchanged there were visible metal particles from the RFID tag antenna in the material. Due to the higher melting point of metal this led to the fragments becoming embedded in the recycled plastic pellets.

The study concluded that the presence of the metal fragments does cause material inconsistencies in the recycled PET and would be undesirable in food packaging applications, particularly transparent packaging. Potential routes to mitigate these impacts includes adding a screen after extrusion to filter out fragments before granulation.[12]

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[12] Influence of RFID tags on recyclability of plastic packaging - ScienceDirect

While spurious tags likely will not detrimentally impact a recycling stream, for single-use packaging the use of a water-based adhesive is essential, ensuring the tags can be separated easily during the caustic washing process prior to the extrusion. For reusable packaging adhesives will need to be detachable only after the packaging has reached an end-of-life stage, UV or heat treatment can be utilised as an option for this. Released tags could then be separately chemically recycled or incinerated.

Chemical recycling

Flaked PET bottles and RFID tags were depolymerised using a solution containing ethylene glycol as a solvent and 1,8-Diazabicyclo[5.4.0]undec-7-ene as an organic catalyst. A single-PET bottle with an RFID tag was depolymerised to bis-(2-hydroxyethyl) terephthalate, BHET monomer, in flasks placed in a preheated oil bath. The reaction obtained a high conversion rate of over 90% PET into BHET which can then be utilised to be repolymerised into virgin quality polymers. This depolymerisation process was then scaled up to 30 bottles and tags, the BHET conversion rate achieved was comparable at 90.2%.

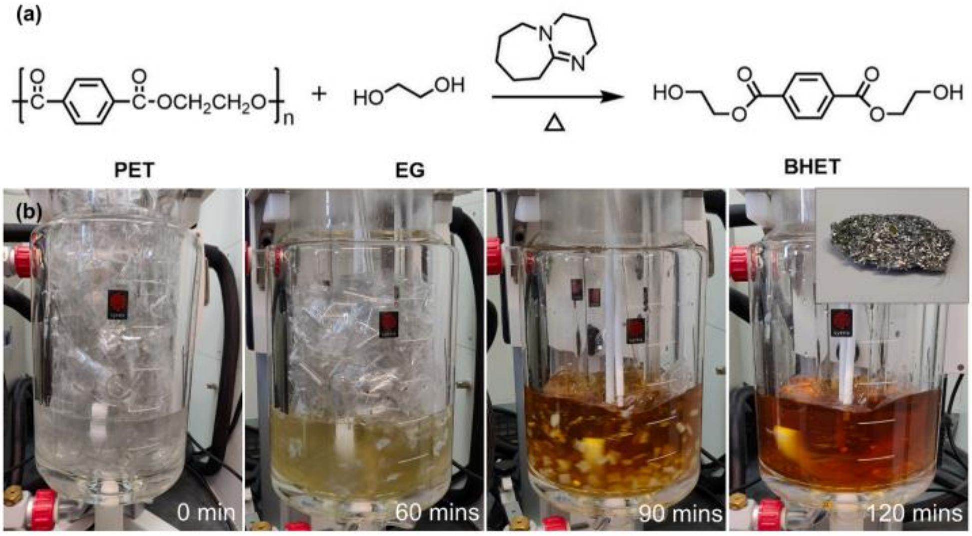


Figure. 22. (a) Conversion of PET to bis-(2-hydroxyethyl)terephthalate (BHET) in the presence of solvent and organocatalyst and (b) Large-scale depolymerisation of PET bottles and RFID tags over time (inset: recovered aluminium). (source: Ahamed et al, 2024[11])

If tags are removed during the washing phase of recycling then there is the option to recycle them separately. The study also looked at this and found that for depolymerisation exclusively for the RFID tags had a conversion rate of 93.5% PET to BHET with the metal fraction also recovered after washing with acetone.

The greatest advantage of chemical depolymerisation is its ability to function in the presence of foreign materials, including the components of RFID tags, metals, other plastics, adhesives, additives, and fillers. This system demonstrated excellent resistance to contaminants, even at large-scales. As this work was conducted as a proof-of-concept model study for the chemical recycling, via depolymerisation, of PET bottles with RFID tags, optimisation of the process would be expected to further improve efficiency.

5.4 Conclusions

There are different end-of-life options for RFID tags dependant on whether they are recycled as a standalone entity or as a component of plastic packaging. If recycled as a standalone entity, then the best route for recycling is through a chemical recycling process. If recycled as part of the packaging then the preferential route is to remove the tag before the plastic recycling process to avoid potential contamination, although plastic packaging can be either mechanically or chemically recycled containing an RFID tag.

The effect of RFID tags on the mechanical and chemical recycling processes is minor. The presence of metal fragments in recycled pellets suggests either material screens would be needed or, preferably, an adhesive used that is readily removed in washing steps. Chemical depolymerisation of either PET bottles with tags, or the tags themselves, was readily achieved with high conversion to monomer BHET and facilitating easy metal recovery. Scaled-up depolymerisation of 30 bottles achieved 90 % conversion, validating the potential scalability of the depolymerisation process.

6. Summary of Findings & Recommendations

Heat Durability

- Packaging does not need to be overengineered, thin-walled containers (HDPE, PP, cPET) performed well in washing tests (apart from Thin-walled PET).
- Ridges effectively preserve packaging rigidity against washing cycle deformation while helping maintain a lower material mass.

Adhesion tests

- NFC tags remain attached and continue to function after multiple washes.
- The tag's location affects the adhesion and it is recommended to avoid ridges, seams and highly curved surfaces when possible.
- Circular tags show good adhesion.

Allergens

- The washing process is able to remove the presence of allergens.
- Using a proven methodology such as ELISA testing is recommended to test for allergen removal.

Reconditioning

- A heat gun and a manual process was found to achieve the best results for reconditioning packaging that had been scratched.

Staining

- Natural PP and HDPE are unsuitable for highly staining products, particularly tomato and turmeric-containing foods.
- Coloured containers tested did not show staining (cPET sample tested). This does not imply there is no diffusion into the polymer but colouration is not detectable.

Sorting

- RFID must be configured to ensure coverage over the entire conveyor area, accommodating all possible tag positions and orientations ensuring each individual surface area is thoroughly scanned.
- Strategic placement of tags on the packaging is required to enhance the sorting system's reliability. This ensures that tags remain within the optimal read volume, reducing the chances of sortation failures and improving overall efficiency.

Recyclability

- There are different end-of-life options for RFID tags dependant on whether they are recycled as a standalone entity or as a component of plastic packaging.
- If recycled as a standalone entity, then the best route for recycling is through a chemical recycling process.
- If recycled as part of the packaging then the preferential route is to remove the tag before the plastic recycling process.

7.Appendices

Appendix 1: Polymer applications, characteristics & limitations

Polymer	Typical packaging applications	Manufacturing processes commonly used	Characteristics	Limitations	Recyclable via current infrastructure
Polypropylene (PP)	Food and non-food pots, tubs, trays, pails etc.	Injection Moulding Blow moulding Thermoforming	Rigid Opaque/transparent Good stability at high temperatures Excellent resistance to acids & alcohols Melting point 135-165 (dependant on homo or co polymer) Good resistance to environmental stress cracking	Sensitive to microbial attacks such as bacteria and mould Limited resistance to aromatic and halogenated hydrocarbons and oxidising agents Poor resistance to UV and scratches	Yes
Polyethylene Terephthalate (PET)	Food and non-food pots, tubs, trays, jars and bottles	Blow moulding Injection moulding Thermoforming	Strong and Lightweight Good gas and moisture barrier properties Suitable for transparent applications Shatter resistant Excellent resistance to alcohols, oils, grease and diluted acids	Amorphous PET has low heat tolerance	Yes
Polybutylene Terephthalate (PBT)	Consumer goods	Injection moulding	Engineering plastic Excellent stain Resistance High strength, toughness and	High mould Shrinkage Poor resistance to hydrolysis (sensitive to hot water)	No

			stiffness Good durability under thermal stress and harsh chemical environments Good UV resistance Low moisture absorption	Prone to warping due to high differential shrinkage	
Polyethylene (High Density) (HDPE)	Jerrycans, chemical drums, personal and healthcare bottles, milk bottles	Easy to process by most methods; used particularly for injection and blow moulding	Translucent/waxy Appearance Weatherproof Good low temperature resistance Good chemical Resistance High tensile strength Excellent moisture barrier properties Melting point 120-140 ̊C	Poor UV and low heat resistance Susceptible to stress Cracking High mould Shrinkage Poor resistance to Hydrocarbons Lower stiffness than PP	Yes
Tritan ™	Water bottles, cosmetic packaging	Injection Moulding Injection stretch blow moulding	Excellent stain Resistance Impact and shatter Resistant Transparent High chemical Resistance Excellent resistance to washing	None found in literature search	No

(Sources of information: Interviews, Selection Guides: Polymers & Plastics (specialchem.com); Thermoplastics (bpf.co.uk))

Appendix 2: Scratched polymer plates for allergen testing

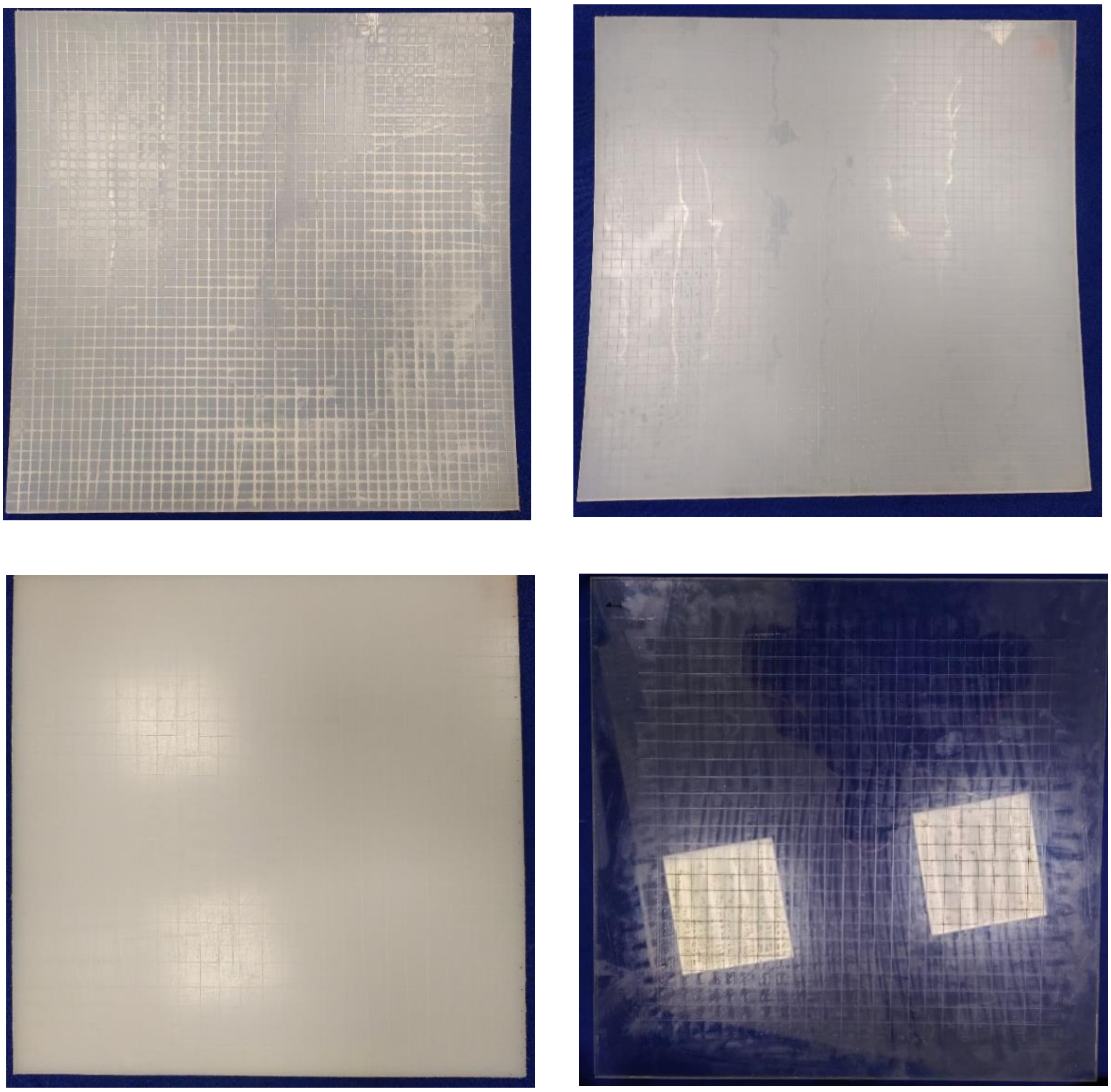
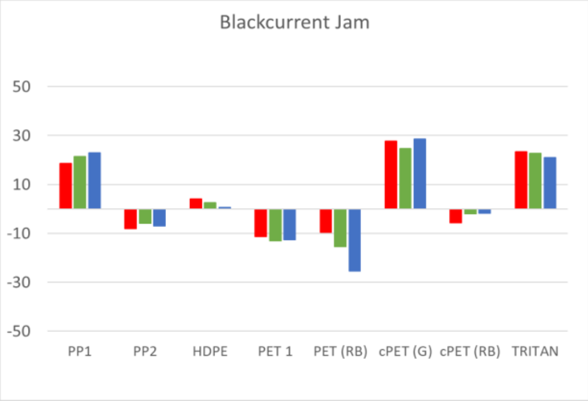
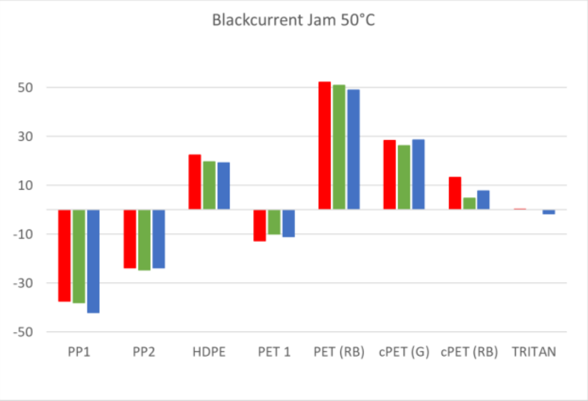


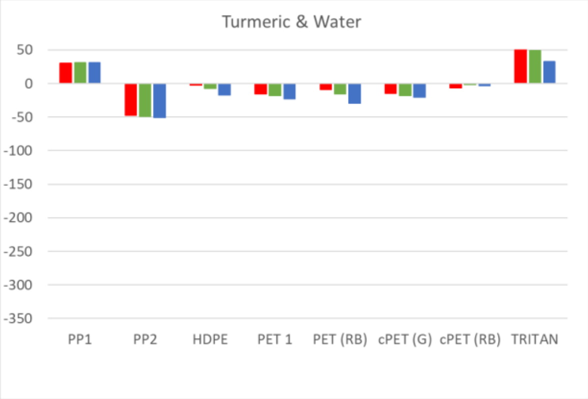
Figure 83. Scratched plates used for ELISA peanut testing. (a) HDPE, (b) PP, (c) Triton (d) PET. The scale bar in all images is 10 cm

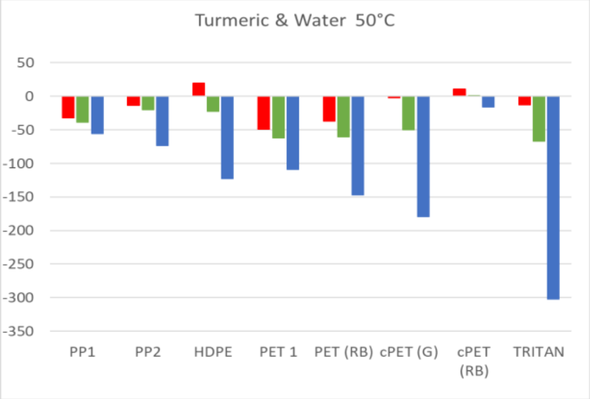
Appendix 3: Polymer staining results

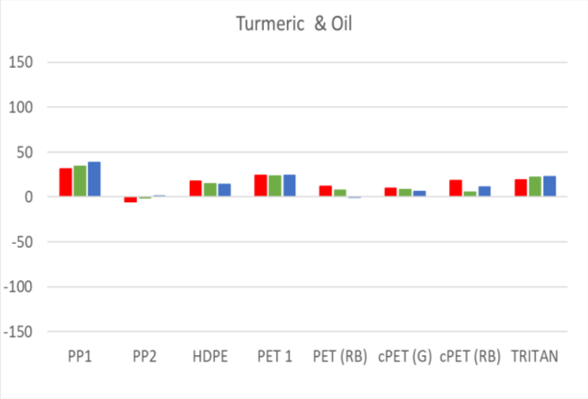
Room temperature and 50 °C data

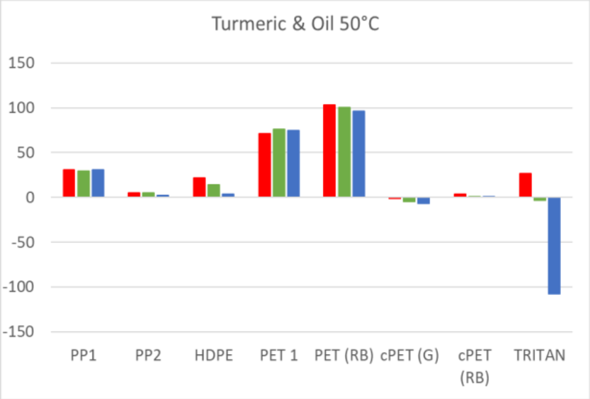


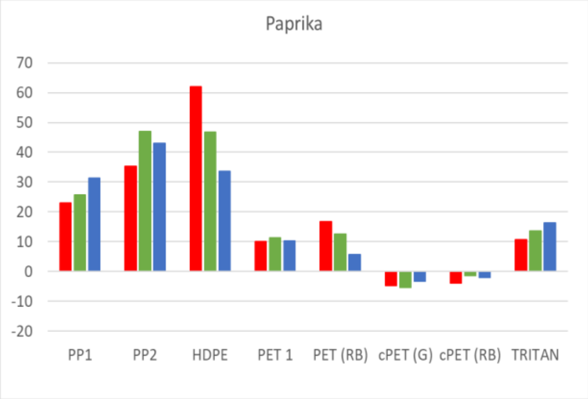


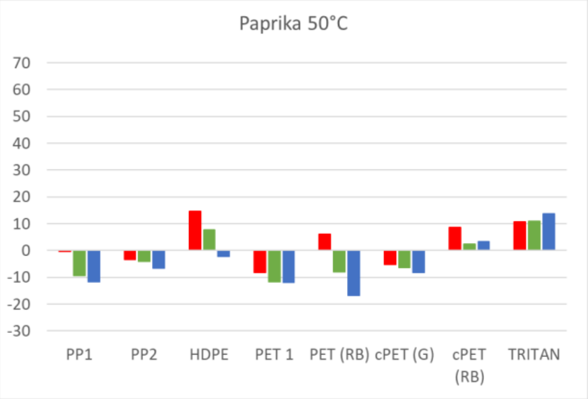


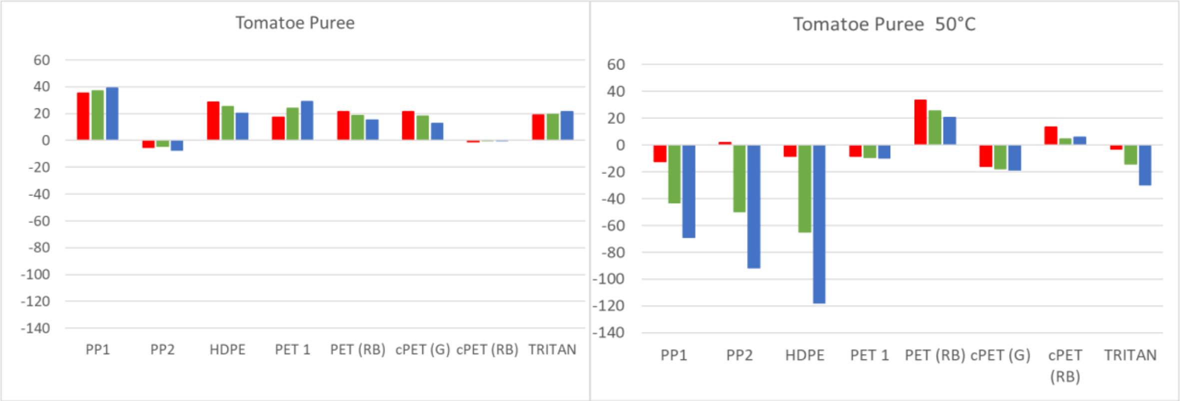








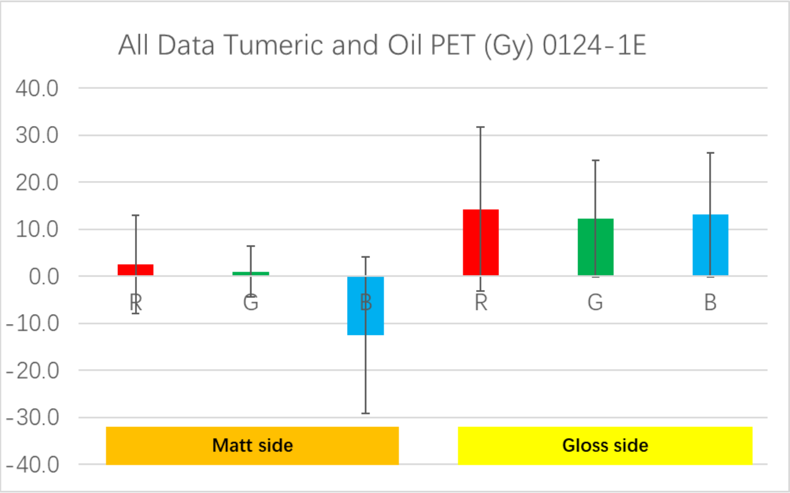




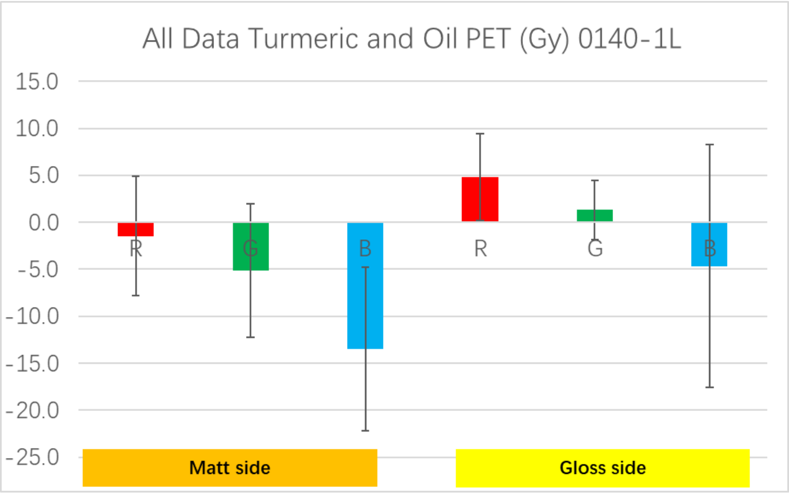
Long-term room temperature data on pigmented systems.

Turmeric and Oil

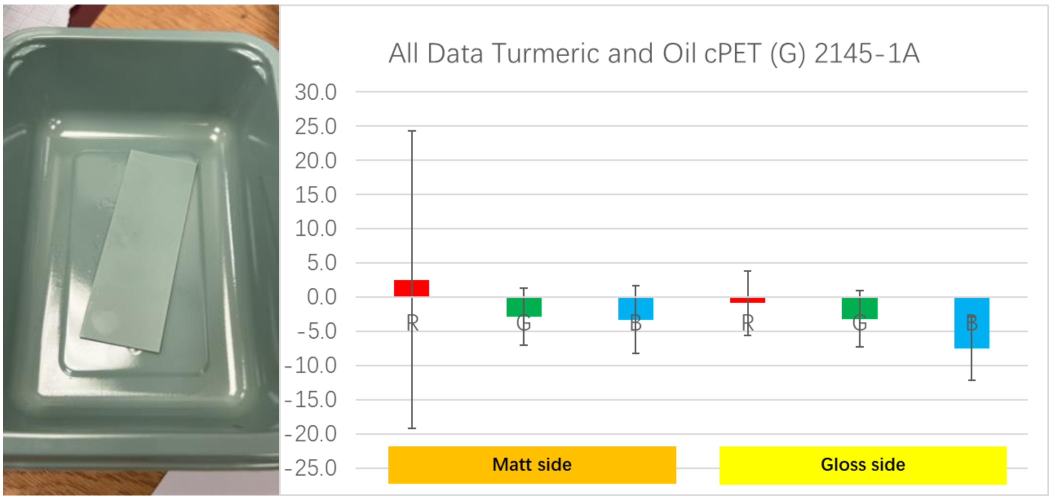
Turmeric and Oil Room temperature tests. Immersed for 83 days



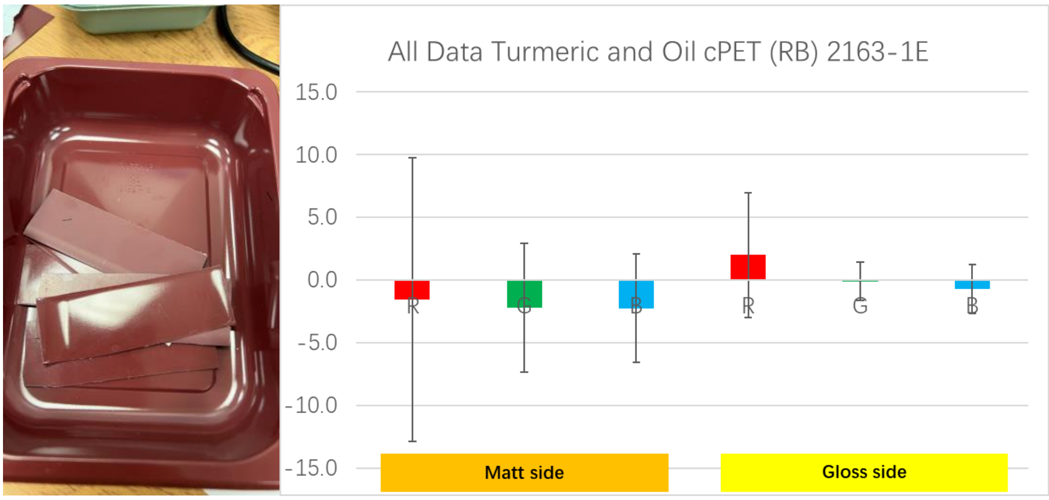
Turmeric and Oil Room temperature tests. Immersed for 84 days



Turmeric and Oil Room temperature tests. Immersed for 84 days

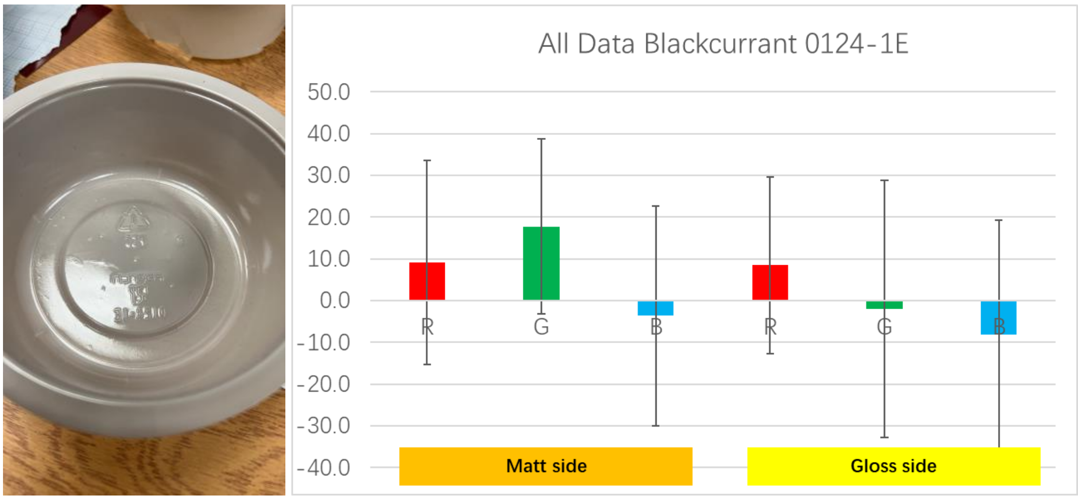


Turmeric and Oil Room temperature tests. Immersed for 88 days

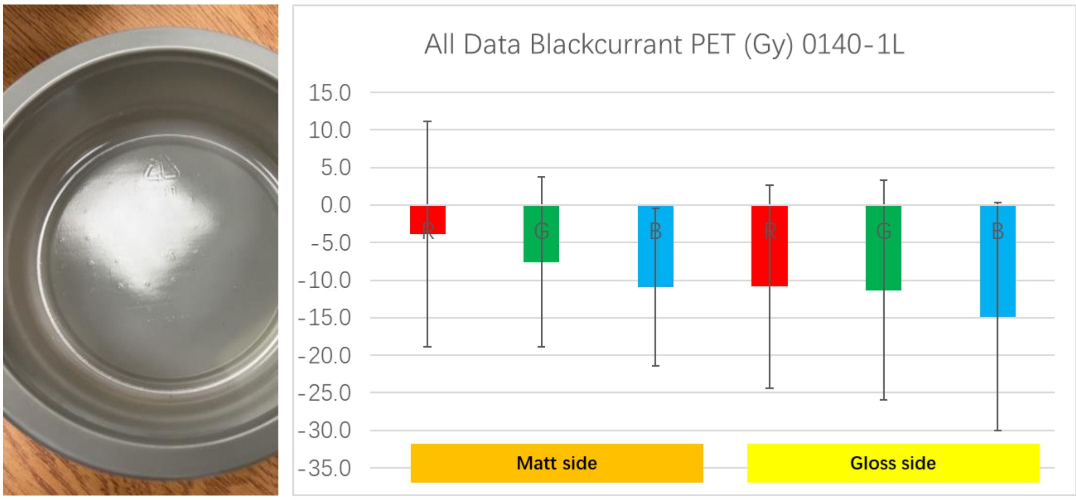


Blackcurrant

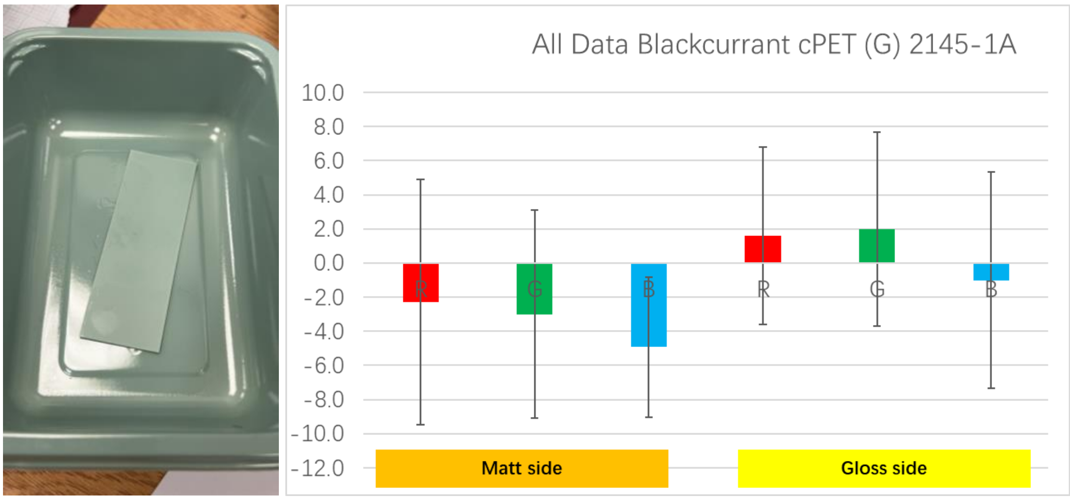
Undiluted Blackcurrant drink, Ribena® Room temperature tests. Immersed for 83 days



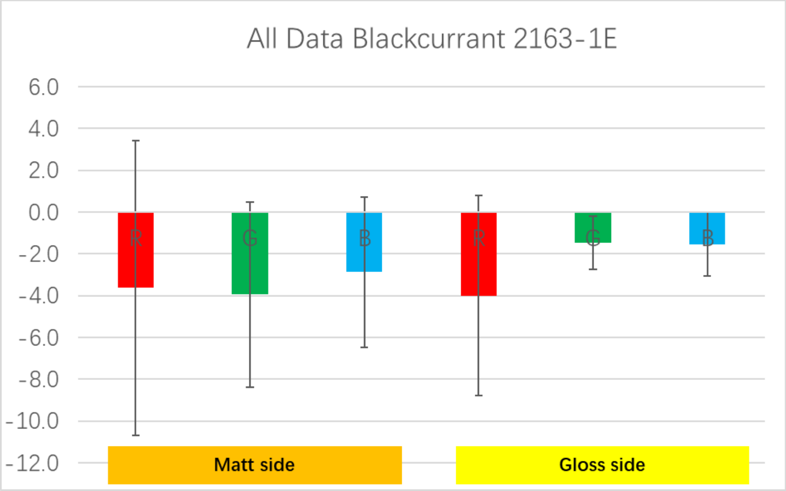
Undiluted Blackcurrant drink, Ribena® Room temperature tests. Immersed for 84 days



Undiluted Blackcurrant drink, Ribena® temperature tests. Immersed for 84 days



Undiluted Blackcurrant drink, Ribena® temperature tests. Immersed for 88 days


All Data Blackcurrant 2163-1E
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
R
G
B
R
G
B
Matt side
Gloss side

Acronyms & Abbreviations

AMRC - Advanced Manufacturing Research Centre

BHET - Bis-(2-hydroxyethyl) terephthalate

cPET - Crystalline Polyethylene Terephthalate

ELISA - enzyme-linked immunosorbent assay

FEP – Fluoroethylene propylene

FlexIC – Flexible Integrated Circuit

HDPE – High-Density Polyethylene

HVM - High-Value Manufacturing

IC – Integrated Circuit

LCA – Life Cycle Assessment

NFC – Near Field Communication

PBT – Polybutylene Terephthalate

PEEK – Polyether Ether Ketone

PET – Polyethylene Terephthalate

PP – Polypropylene

Ppb – Parts per Billion

PS – Polystyrene

PTFE – Polytetrafluoroethylene

PVC – Poly Vinyl Chloride

RECOUP – RECycling Of Used Plastics Ltd

RFID - Radio Frequency Identification

RGB – Red, Green & Blue

TMB - 3,3’,5,5’-tetramethylbenzidine

TRACE - Technology-enabled Reusable Assets for a Circular Economy

UKRI - UK Research & Innovation

UV - Ultraviolet

RECOUP Leading a more circular plastics value chain

www.recoup.org

Pragmatic

www.pragmaticsemi.com

University of Sheffield

www.sheffield.ac.uk

AMRC Cymru

www.amrc.co.uk