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# Surveys of Plastics in Post-1950 Non-published Book Collections

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**Abstract:** Research over the past three decades has demonstrated that certain plastics in cultural materials are inherently unstable, displaying short lifespans and accelerating the degradation of neighbouring collection materials. Knowledge of the conservation of plastics is increasingly common in museum settings. However, less information is available on conserving plastics found in paper-based collections, and even less guidance on the materials and deterioration of plastic components found in book and document bindings. As plastics have been present in popular bookbinding materials since the mid-twentieth century, collection care professions require knowledge and methods for preserving these materials entering book collections. The aim of this paper is to determine strategies for the care of post-1950s books containing plastic. Collection surveys were conducted to determine the materials, structures, and degradation patterns of non-published books found in archive and archive-like settings at the South Australian Museum, the Art Gallery of New South Wales, and the Grimwade Centre for Cultural Materials Conservation at the University of Melbourne. A methodology combining condition reporting and infrared spectroscopy identified six plastic polymers in 35 binding styles that are summarised as 10 binding types. Recommendations are made for the use of preventive storage strategies responding to four categories of damage.

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**Keywords:** archives, book collections, book structures, plastic identification, plastic degradation, collection surveys, infrared spectroscopy

**Zusammenfassung:** Die Forschung der letzten drei Jahrzehnte hat gezeigt, dass bestimmte Kunststoffe, die bei Kulturgut Verwendung fanden, von Natur aus instabil sind, eine kurze Lebensdauer aufweisen und den Abbau in Kontakt gelagerter Sammlungsmaterialien beschleunigen. Das Wissen über die Konservierung von Kunststoffen ist in Museen zunehmend verbreitet. Es gibt jedoch weniger Informationen über die Konservierung von Kunststoffen in papierbasierten Sammlungen und noch weniger Hinweise auf die Materialien und den Verfall von Kunststoffkomponenten in Buch- und Dokumenteneinbänden. Da Kunststoffe seit Mitte des zwanzigsten Jahrhunderts in gängigen Bucheinbänden vorkommen, benötigen Sammlungspfleger Kenntnisse und Methoden für die Konservierung dieser Materialien, die in Buchsammlungen Eingang finden. Ziel dieser Arbeit ist es, Strategien für die Pflege von Büchern aus der Zeit nach 1950, die Plastik enthalten, zu ermitteln. Es wurden Sammlungserhebungen durchgeführt, um die Materialien, Strukturen und Abnutzungsmuster von unveröffentlichten Büchern in Archiven und archivähnlichen Einrichtungen des South Australian Museum, der Art Gallery of New South Wales und des Grimwade Centre for Cultural Materials Conservation der Universität Melbourne zu ermitteln. Mit einer Methode, die Zustandsberichte und Infrarotspektroskopie kombiniert, wurden 6 Kunststoffpolymere in 35 Einbandarten identifiziert, die zu 10 Einbandtypen zusammengefasst werden. Es werden Empfehlungen für den Einsatz präventiver Lagerungsstrategien gegeben, die 4 Schadenskategorien entsprechen.

**Stichworte:** Archive, Buchbestände, Buchstrukturen, Kunststoffidentifikation, Kunststoffabbau, Sammlungserhebung, Infrarotspektroskopie

## 1 Introduction

Bookbinding as a practice is no exception to the ubiquitous use of mouldable synthetic polymeric materials, more commonly known as plastic. Book cloth with synthetic additives have been commercially successful beginning in the mid-20th century (Lundblad 2015). Spiral and post bindings found in scrapbooks and photographic albums contain plastic spines (Teper 2008). Wire bindings of manuscripts and manuals may have plastic covers (Chu and Knight 2023). Few commercially bound books today are produced without plastic components in the adhesives, spines, paper coatings, or covering materials. However, there is little published on the specific polymers, binding structures, and degradation patterns of books containing plastic, to enable appropriate conservation care when these books are found in libraries and archives.

It is now commonly recognised that modern polymeric materials like plastic require conservation care, just as with traditional materials. Collection surveys in museums and galleries since the 1990s have shown that certain plastics in cultural materials are particularly unstable, displaying short lifespans and accelerating the degradation of neighbouring collection materials (Lavédrine, Fournier, and Martin 2012; Shashoua 2008). Cellulose nitrate (CN), cellulose acetate (CA), plasticised polyvinyl chloride (PVC-P), also known as vinyl, and polyurethane (PUR) foam are recognised as the four so-called ‘malignant’ plastics that merit higher priority in collection care (Williams 2002). Separation from other materials, cold storage, and acid scavengers are examples of conservation methods used to manage the dramatic deterioration of these plastics.

It is unclear if the plastics used in bookbinding are unstable, and if so, what steps should be taken to manage deterioration in contemporary book collections. A questionnaire survey conducted in 2019 reported that more than 90% of Australian archives contain plastic bindings, with approximately 50% in poor condition (Chu and Nel 2023). Questionnaire results indicated the need for further research into the identification, condition, and conservation of plastics in paper-based collection settings. The aim of this paper is therefore to determine strategies for preserving books containing plastic, based on collection surveys of non-published book collections in archive and archive-like settings in Australia. It is hoped that results may inform conservators and others in collection care roles in identifying material types and choosing conservation strategies relevant to books containing plastic.

## 1.1 Plastics in Bookbinding

The introduction of plastics in bookbinding may be contextualised in the rise of industrial automation and production in the 19th century. In this period, the book industry adapted to meet the rapidly growing demand for printed material through the development of automated papermaking, printing, and sewing machines. Case bindings were introduced around the 1820s, increasing the efficiency of mass book production by allowing for covers to be prepared separately from the printed textblock (Cockerell 1971, 19; Twyman 1994, 231). Book cloth could be easily decorated with machine stamping, and were popularly used as a covering material for hardback cased books (Lundblad 2015, 72–73). Around 1910, the first semi-synthetic book material was produced: book cloth impregnated with a CN-based filler called pyroxylin (Garside and Knight 2018). CN-based imitation leathercloths, which are fabrics stamped with artificial textures to resemble leather, were commercially produced by the mid-20th century under brands such as Rexine®, Pegamoid® and Arbetex® (Lipscombe 2016; Lundblad 2015, 72; Moncur 1962). Additional plastics have been found in book cloth in a

recent survey using infrared (IR) spectroscopy, identifying the polymers CN, CA, and acrylic or poly(methyl methacrylate) (PMMA) (Garside and Knight 2018). However, the precise periods of use for each polymer are not presently documented.

Adhesive-only binding, also known as perfect binding, was developed around the same point in history and with a similar structure as case bindings. In this style, adhesive is applied to the spine-side of loose single-sheet pages and directly cased-in to a cover, normally made of paper card, eliminating the need for the labour-intensive hardcover construction, paper folding, and sewing steps. First patented in 1836 as ‘caouchouc’ bindings, the style was temporarily abandoned in the 1870s due to the tendency of failure in the rubber-based adhesives (Pearson 2013, 247; Twyman 1994, 231). Decades later in the 1950s, adhesives made of hot-melt ethylene-vinyl acetate (EVA) and cold-emulsion polyvinyl acetate (PVAc) were introduced as the first fully synthetic materials in book-binding (Blaxland 1994). These adhesives provided the needed flexibility and strength to the book spine. PUR-based adhesives were later introduced around the 2000s, claiming greater stability and strength (Rebsamen 2002). Technically, perfect binding specifies an adhesive binding in which the covers are flush with the textblock (Rebsamen 2003, 3), but today the term is generally applied to any adhesive-only binding.

In the early 19th century, photographic albums were invented for the storage of increasingly accessible and diverse photographic prints. Thermoplastic has been described as possible materials for covers of *carte-de-visite* albums that appeared after the 1860s (Horton 1999, 16–17). Considering the time of production, these covers would likely be one of the earlier semi-synthetic polymers, CN or CA. By the 20th century, many scrapbooks were bound using punch-and-bind styles, such as post, ring, and spiral bindings, in which loose sheets are punched through to create holes, then secured. These structures allow for some of the important features of scrapbooks: expansion of the spine width to fit the inserted contents, flexibility in the pages or spine opening for viewing and access, and removable pages (Teper 2008, 51). Plastic spines are known to be used in post and spiral bindings (Teper 2008; Zucker 2011), but further details on the polymer types and periods of use are not presently documented. Plastic pocketed sleeves made of polyethylene (PE) or PVC were introduced for ring-bound albums by the 1980s, although one source states as early as the 1960s (Horton 1999, 19; Teper 2008, 51). Beyond scrapbooks, punch-and-bind styles are popular in contemporary on-demand binding, and may additionally include plastic sheet covers made of PVC, polypropylene (PP), or polyester, also known as polyethylene terephthalate (PET) (Chu and Knight 2023).

Lastly, a book may even contain plastic in the paper components. Synthetic papers were in development throughout the 20th century, beginning with cellulose-based papers given synthetic coatings and sizes. By the 1970s, resin coated papers with PE and PP layers were available for photographic prints, and by the 1980s, technology had progressed to fully synthetic paper-like materials with no cellulose

paper component (Jürgens 2009, 44–47). Driven by the goal of easily printable papers, synthetic papers were adapted to inkjet printing using calcium- or silica-based coatings by the 1990s, then used in book covers and dust jackets by the 2000s (Mustalish 2007). Published books and stationery notebooks containing synthetic paper textblocks were commercially available by the 2000s and 2010s respectively (Chu and Nel 2019, 39). Polymers used in synthetic papers are frequently changing and often proprietary, but have included CA, PE, PP, PVC, PUR, PVAc, and polystyrene (PS), with the most common being PP (Mustalish 2007).

## 1.2 Previous Surveys of Book and Paper Collections

Throughout the history of book conservation, collection surveys have been used to inform future institutional strategies (Bruce 1982), to compare structural variations within a subset of books (Rhodes 1995), and to investigate degradation causes (Alshibly, Alzamily, and Fazil 2019; Mesquita et al. 2009). A recent development in the documentation of survey data is the introduction of linked data. Pioneered in a survey of Byzantine bindings, the data structuring approach uses standardised terminology in linked fields to enable data storage in a resilient, future-proof format (Velios and Pickwoad 2005). This project was since developed into an open language thesaurus (Velios and Pickwoad 2020), and further adapted for the surveying of Ethiopian bindings (Sasso 2022).

Prior to the current project, two collection surveys in archives and libraries have been conducted in response to the increasing amounts of plastics in these collections. A survey on book collections conducted in Prague at the National Library of the Czech Republic (NLCR) revealed six plastics used in books and book attachments dating from the 19th century onwards: CN, CA, PE, PUR, PVC and PMMA (Vávrová et al. 2021). Another survey of an artist's archive containing mixed materials dating from 1960 to 1990 at New York University Libraries (NYUL) identified an additional five plastics (Stein et al. 2021): PVAc, PET, PS, acrylonitrile butadiene styrene (ABS), and urea-formaldehyde (UF). Both surveys made use of non-invasive IR spectroscopy for identification.

For the practicing conservator, the surveys at NYUL and NLCR may provide general guidance on the types of plastic polymers that may be present in libraries and archives. However, two factors curb the application of the findings for specific collections or items:

1. There is limited description of the physical form of the identified plastics. It is not clear from these two articles which types of collection items contain which polymer, nor are there descriptions of physical features that would aid in identification. Physical descriptions of plastics are a vital supplement to identification processes since access to analytical equipment is not widespread in collection

- settings. Linking physical features and analysis results can act as a reference for non-instrumental identification.
2. There is limited guidance on storage, monitoring, and treatment for the identified book plastics. The NYUL article provides recommendations for the storage of each malignant plastic, but the contents appear to be targeted to the three-dimensional objects in the archive and not specific to book items. Those wishing to care for plastics in books must independently formulate collection care strategies. Such research requires time and expertise that may not be available in all collection settings.

Thus, although these two surveys shed light on the types of plastics in paper-based collections, additional work is necessary to aid in non-analytical identification and practical collection care recommendations for plastics in books. This paper draws on the approaches of these past collection surveys to address the two listed knowledge gaps. Working within a subset of book types, the survey is conducted with standardised terminology in relationally-structured fields allowing for the visualisation of connections between data, with the aim of informing future treatment strategies.

## 2 Methods

### 2.1 Collections Surveyed

Three collections were chosen to provide a broad selection of non-published books containing plastic collected in Australia: a museum archive, a gallery artwork, and an academic archive (Table 1). ‘Non-published books’ is used in this paper to refer to books that are not published, to distinguish them from ‘unpublished books’ that may suggest an intention for eventual publication.

1. The archive of the South Australian Museum (SAM) in Adelaide was surveyed in 2019. The museum’s archive collection is predominantly paper-based, but includes a mixture of historical objects and textual, audio-visual, and digital records

**Table 1:** Details of surveyed Australian collections.

| Institution                                         | Collection type                     | Collection period | No. of items surveyed   |
|-----------------------------------------------------|-------------------------------------|-------------------|-------------------------|
| South Australian Museum                             | Manuscripts, photo albums           | 1980–2010         | 12 ( <sup>a</sup> 83)   |
| Art Gallery of New South Wales                      | Artwork <i>Chinese Bible</i> (2009) | 1949–1999         | 105                     |
| Grimwade Centre for cultural materials conservation | Theses                              | 1982–2019         | 48                      |
| <b>Overall</b>                                      |                                     | 1949–2019         | 165 ( <sup>a</sup> 236) |

<sup>a</sup>Additional plastic-containing items were surveyed at SAM, but only the 12 books are discussed in these results.

dating from the mid-19th century onwards (South Australian Museum 2020). A selection of mixed-format plastics was surveyed, but only the results of the 12 books will be presented in this paper, except for the one instance of Table 4 in Section 4.

2. An artwork at the Art Gallery of New South Wales (AGNSW) in Sydney was surveyed in 2019. The artwork *Chinese Bible* (2009) by Yang Zhichao is a performance installation work featuring 3000 notebooks made in China. The collection features a large range of plastic notebook cover styles available in the period of 1949–1999. The archive-like nature of the conservation and cataloguing of this large collection of unique notebooks has been described by conservators working on this artwork (Bunn 2018).
3. The thesis archive of the Grimwade Centre for Cultural Materials Conservation (GCCMC) at the University of Melbourne was surveyed in 2021. The thesis archive of GCCMC contains a comprehensive record of student theses and was chosen for its variety in low-cost plastic binding styles available in Australia.

Note that the place of manufacture of the surveyed materials, other than that of *Chinese Bible*, is not clear. Collections in Australia often contain internationally manufactured materials. Even going back to the early history of bookbinding in Australia in the 19th century, bookbinding materials were mostly imported (Mills 1998). Note also that while the collections at SAM and GCCMC are both archives containing books, the collection at AGNSW is an artwork with the physical form and cataloguing needs of an archive, but not precisely an archive. Collection types surveyed may not reflect collecting patterns in large archives and libraries, but rather non-published book collections in archive-like settings. Plans to survey additional collections were impacted by COVID-19 safety restrictions.

## 2.2 Sample Selection and Workflow

Sample items were selected from the respective collections to provide a representation of plastic types, binding features, and condition. As two of the collections were not catalogued on the level of individual items, it was not possible to perform systematic selection or random sampling based on the existing documentation. Sample selection relied on the knowledge of the conservators and collection managers working at the institutions.

1. At SAM, surveying was conducted by a team of three consisting of two archive collection managers working at SAM and a visiting conservator-researcher. Due to time constraints, the survey scope was limited to the amount of data that could be collected in 10 working days. Before surveying began, the researcher adapted

a list of common archive formats containing plastics based on the work of Calmes (1993), since the original aim of the survey was to encompass all formats. The collection managers chose collection items based on the list of formats and retrieved them from the storage areas to a surveying space. The first surveying day was spent on a trial of the workflow with the researcher's supervisor. On subsequent days, the collection managers were trained on the documentation workflow and alternated time to conduct documentation, while the researcher conducted polymer identification and photography in parallel (see details in following sections). Verification and standardisation of the collected data was conducted by the researcher at the end of each day. Book items were selected post-survey for discussion in this paper.

2. At AGNSW, surveying was similarly conducted by a team of three over 10 days, but the team consisted of two conservators working at AGNSW and the same visiting conservator-researcher. Conservator A was familiar with the collection while Conservator B was familiar with the documentation workflow. The collection was transported by the AGNSW logistics team to the surveying site before the surveying period. On the first surveying day, books with unique forms and deterioration were selected from the storage boxes based on a visual survey by Conservator A and the researcher, then Conservator A was trained on the documentation workflow over the course of the survey. Like the SAM survey, the two conservators alternated time to conduct documentation, while the researcher conducted polymer identification and photography in parallel. Data verification and standardisation was conducted by the researcher at the end of each day.
3. At GCCMC, surveying was conducted by the conservator-researcher only and limited to five working days due to access restrictions impacted by COVID-19. On the first day, an initial visual survey was conducted in the storage area to identify the time periods and types of deterioration represented. The represented period was then divided into 5-year spans, and five books from each period were retrieved to represent the binding styles and deterioration observed. The researcher conducted visual documentation, polymer identification, and photography over the remaining days. Data verification was conducted at the end of each day.

## 2.3 Documentation

A collection survey methodology was developed utilising controlled vocabularies, and standardised photographic documentation and analytic measurement parameters. Details of the methodology have been previously described as applied to a broader plastics project with an emphasis on three-dimensional museum objects

(Bell, Nel, and Stuart 2019; Bell et al. 2022). An overview is provided here of the adapted methods for book collections.

A template was created in a spreadsheet editing application with column headings for each data field and rows for each surveyed item, accompanied by a data entry guide describing possible values and formats for each field. A list of all fields and terminology used is included in the Appendix as Tables A1 and A2. When adapted for this book survey, descriptions of the binding structures were initially placed in the open-text object description field, then later transferred to book-specific fields for ‘binding type’ and ‘binding subtype’. Controlled vocabulary for the visible degradation types originated from terminology used during the plastics surveys conducted by the POPART project across three European museums (Barabant 2012; Keneghan et al. 2012), and refined in an iterative process to include only relevant terms for books.

To quantify degradation, a four-point scale was used to rate the overall condition on an item level, and each visible degradation type on a component level. These rankings were also based on those used in the POPART surveys (Keneghan et al. 2012, 118):

- 1: Slight and limited.
- 2: Perceptible and moderate.
- 3: Obvious and considerable.
- 4: Important and general.

Digital photography was used in addition to the template for visual documentation of object appearance, degradation, and analysis sites (see Section 2.4). Template data was processed in Microsoft® Excel for Mac 16.63.1 (22071301). Visualisations of the quantitative data were created with the data visualisation library Seaborn 0.11.1. Stylised diagrams of the book structures were created in Microsoft® PowerPoint for Mac 16.63.1 (22071401).

## 2.4 Polymer Identification

Accompanying a visual examination of the materials and inscriptions, plastic polymers in each component of an object that appeared to be manufactured independently were identified with Fourier-transform infrared (FTIR) spectroscopy with attenuated total reflection (ATR). This fast and non-invasive technique was chosen following the use of IR spectroscopy in collection surveys at NYUL and NLCR, along with its common use in plastic polymer identification (Bell et al. 2022; Lavédrine, Fournier, and Martin 2012; Stuart 2004). A Bruker ALPHA-P FTIR spectrometer with a diamond ATR module was used in the SAM and GCCMC surveys, while a Thermo Scientific™ Nicolet Summit FTIR Spectrometer with an Everest Diamond ATR

accessory was used in the AGNSW survey. To achieve contact with the window, plastic components were temporarily clamped with the instrument arm. Each reading was conducted with 32 co-added scans at resolution of  $4\text{ cm}^{-1}$  in the range  $4000\text{--}375\text{ cm}^{-1}$ . Data collection was carried out with OPUS software version 7.5.

For polymer identification from the FTIR spectra, three processes were used to confirm the identity of a sample. Where two out of the three processes were in agreement, the identity of the plastic was recorded. Otherwise, the polymer was listed as 'Unknown':

1. A visual observation of the spectrum was carried out in the OPUS 7.5 software, observing known characteristic spectral bands.
2. A search of the Bruker commercial library was used to list algorithm-generated matches with the sample. Similarity levels of above 800 hit quality, along with a visual verification of similarity, were regarded as a positive identification.
3. A search of an in-house reference library of 20 common plastic polymers was used to list algorithm-generated matches with the sample. Similarity levels of above 80% correlation, along with a visual verification of similarity, were regarded as a positive identification.

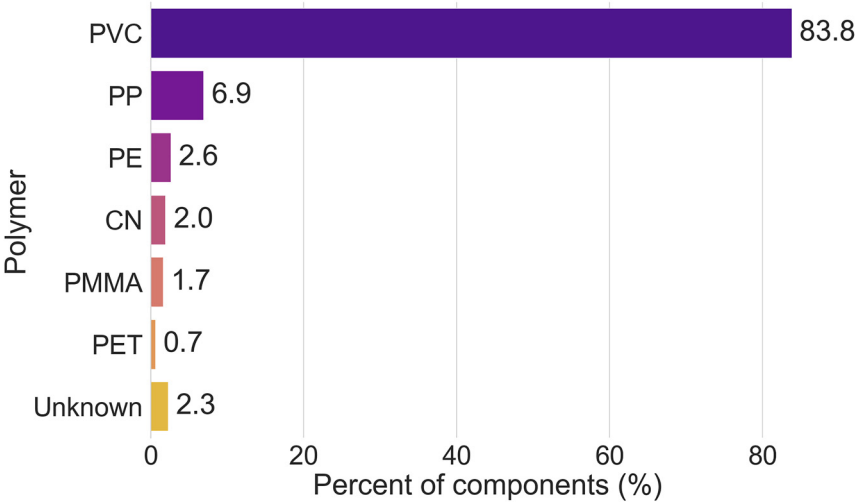
## 3 Results

165 Books were surveyed across the three sites. Of these, 13 items did not contain plastic materials, making a valid total of 152 plastic items with 303 plastic components.

### 3.1 Polymer Types

Six plastic polymers were identified: CN, PE, PET, PMMA, PP, and PVC. Examples of the IR spectra for each polymer, along with an assignment of characteristic bands, are shown in the Appendix as Table A3. Seven plastic components (2.3%) could not be identified using ATR-FTIR due to a lack of access to the component or low contact with the ATR window, resulting in poor or unrecordable spectra. These were adhesives and rigid components with uneven surfaces. For rigid components, external reflection was attempted, but did not yield clear results due to the black or transparent colouration being insufficiently reflective. Polymers that achieved a clear spectrum were readily distinguishable.

When the frequency of identified polymers is compared (Figure 1), PVC is shown to be the most common polymer by a wide margin, at 83.8% of the polymers found. As illustrated in the next section, PVC was found in the widest variety of book components and binding styles, predominantly the covers, spines, and jackets. Manufacture

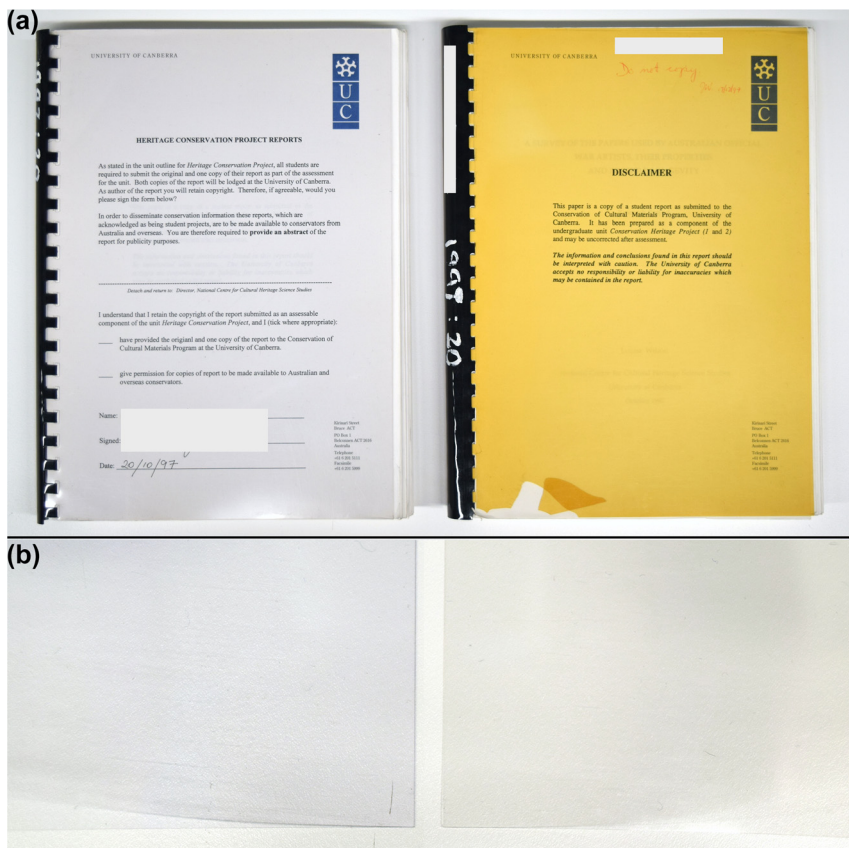


**Figure 1:** Frequency of polymer types found in 303 plastic book components.

processes included cast, film, and sheet form. All PVC components found were plasticised, with widely varying rigidity, transparency, and colouration. PVC tended to have a shiny, oily sheen, and clear PVC had a cool tone unless significantly deteriorated (Figure 2a). Although PVC is also the most common polymer in the NYUL survey at 30.4% (Stein, Pace, and McCann 2021, 3), the relative prominence of PVC in the present survey may be impacted by the large number of books selected at AGNSW (100 out of 152 valid items), consisting of a comparatively uniform collection of notebooks.

PP (6.9%) was the next most common polymer. PP was also present in a variety of colours, components, and forms, such as sleeves and synthetic paper in film form, and strip and ring binding spines in cast form. PP could generally be distinguished from PVC by its lower density and lack of lustre, displaying a waxy rather than oily sheen. When in plastic-only covers, PP sheets were relatively thick, translucent to opaque, and had moulded textures unlike the smooth, clear, and thin PVC covers. In contrast, PVC sleeves were noticeably thicker than PP and PE pocketed sleeves.

Remaining polymers were found in small numbers, and therefore a small number of applications. PE (2.6%) was limited to films like sleeves and bags in ring bindings, while CN (2.0%) was only found as a coating or sizing of book cloth. PMMA (1.7%) was found in both paper and book cloth coatings, and in moulded form for a title plate. PET (0.7%) was limited to sheet form for thermal binding covers, distinguishable from PVC by a warm tone (Figure 2b). Results for each polymer by component type are summarised in Table 2.



**Figure 2:** (a) Two copies of a thesis from the same year and author, with PVC front covers. The cover on the left is shiny and clear while the cover on the right is dull and yellow, with breakage and losses along the tail edge. The difference in deterioration level is likely due to differing storage conditions. Names have been anonymised for privacy. (b) Comparison of clear covers made of PVC (left) and PET (right), displaying cool and warm tones respectively.

### 3.2 Binding Styles

In the survey, 35 binding styles were visually identified, defined as books containing unique physical features or components, such as closures, cover material types, and attachment methods. Binding styles were then categorised into 10 binding types based on the structure of the plastic binding component: encased, comb, thermal,

Table 2: Identified plastic polymers listed by book component.

| Polymer                      | Component  |       |        |       |        |
|------------------------------|------------|-------|--------|-------|--------|
|                              | Book cloth | Cover | Jacket | Spine | Sleeve |
| Cellulose nitrate            | ✓          | –     | –      | –     | –      |
| Polyethylene                 | –          | –     | –      | –     | ✓      |
| Poly(ethylene terephthalate) | –          | ✓     | –      | –     | –      |
| Poly(methyl methacrylate)    | ✓          | –     | –      | –     | –      |
| Polypropylene                | –          | ✓     | ✓      | ✓     | ✓      |
| Poly(vinyl chloride)         | –          | ✓     | ✓      | ✓     | ✓      |

ring, wire, spiral, strip, cord, post, and spring-back (Table 3). Binding type terminology was based on names currently used by commercial retailers (e.g., Officeworks 2023; Staples 2023), with two exceptions:

- ‘Encased’ is an original term here used to encompass both hard and softcover cases.
- ‘Strip’ is used instead of the trademarked ‘VeloBind®’ for congruency with other terms.

Table 3: Descriptions of 10 identified plastic binding types, listed in order of frequency.

| Binding type | Description                                                                                                                                                                            |
|--------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Encased      | Textblock secured with synthetic adhesive and sometimes sewing before casing in. Covers may be paper, plastic, or covered boards (both soft and hardcovers included).                  |
| Comb         | Pronged plastic spine with a circular appearance when seen head-on, inserted like a comb through punched holes along the spine edge of textblock.                                      |
| Thermal      | Spine contains a metallic foil strip coated with heat-activated adhesive. Plastic or paper covers may be applied as one continuous folder or separate sheets.                          |
| Ring         | Plastic or metal spine is composed of multiple rings, one per punched hole, often allowing page removal when opened. Plastic sleeves allow for attachment of non-punched materials.    |
| Wire         | Also known as twin wire and Wire-O™ binding, the spine is a continuous coated metallic wire with a double-loop pattern, inserted into punched holes along the spine edge of textblock. |
| Spiral       | A helix-shaped plastic strip inserted through punched holes and cinched at head and tail.                                                                                              |
| Strip        | Also known as VeloBind®, the plastic spine is composed of two thin strips, one pronged and one flat, secured together with heat through punched holes.                                 |
| Cord         | Plastic or natural fibre cords tied through punched holes along the spine edge of textblock.                                                                                           |
| Post         | Also known as screw-post, metal or plastic screws are driven through punched holes along the spine edge of textblock.                                                                  |
| Spring-back  | Stiff removable boards with metallic spine grip that springs open when boards are pushed at an extreme opening angle.                                                                  |

Apart from encased, thermal, and strip bindings, most featured mechanical-only attachment methods used no adhesive. A stylised diagram is provided summarising the binding structures and identified polymers (Figure 3). PVC was found in all but one binding type.

*Encased bindings* were the most common at 65% of the surveyed books, including both hard and softcover cases (Figure 4a). Plastic materials found in encased bindings were book cloth with CN and PMMA coatings, paper covers with PP and PVC coatings, and solid PVC cases and jackets.

*Comb and ring bindings* were the next-most common at 7.9% each. Comb bindings all featured a PVC spine with curved prongs, along with PVC or PP front covers. Ring bindings had more variation, with either metal or PP rings, and covering materials of PVC-covered boards or solid PP. Ring bindings with PP components were labelled as archival binders, and additionally had PP slipcases. Ring bindings contained PP, PE, and PVC pocketed sleeves with punched holes.

*Thermal bindings* assembled with a metal foil adhesive strip represented 7.2% of the books. Thermal bindings had a variety of cover materials, including PMMA-coated book cloth, PVC-coated paper, and clear PVC and PET covers. Some had matching covers while others had different materials for the front and back. Spine coverings found were PMMA-coated book cloth. Although not the most common binding type, thermal bindings were the only books to feature PET components in the surveyed collections.

*Wire and spiral bindings* (3.3 and 2.6%) had only PVC front covers when plastics were present. Spiral bindings additionally featured solid PVC helix spines.

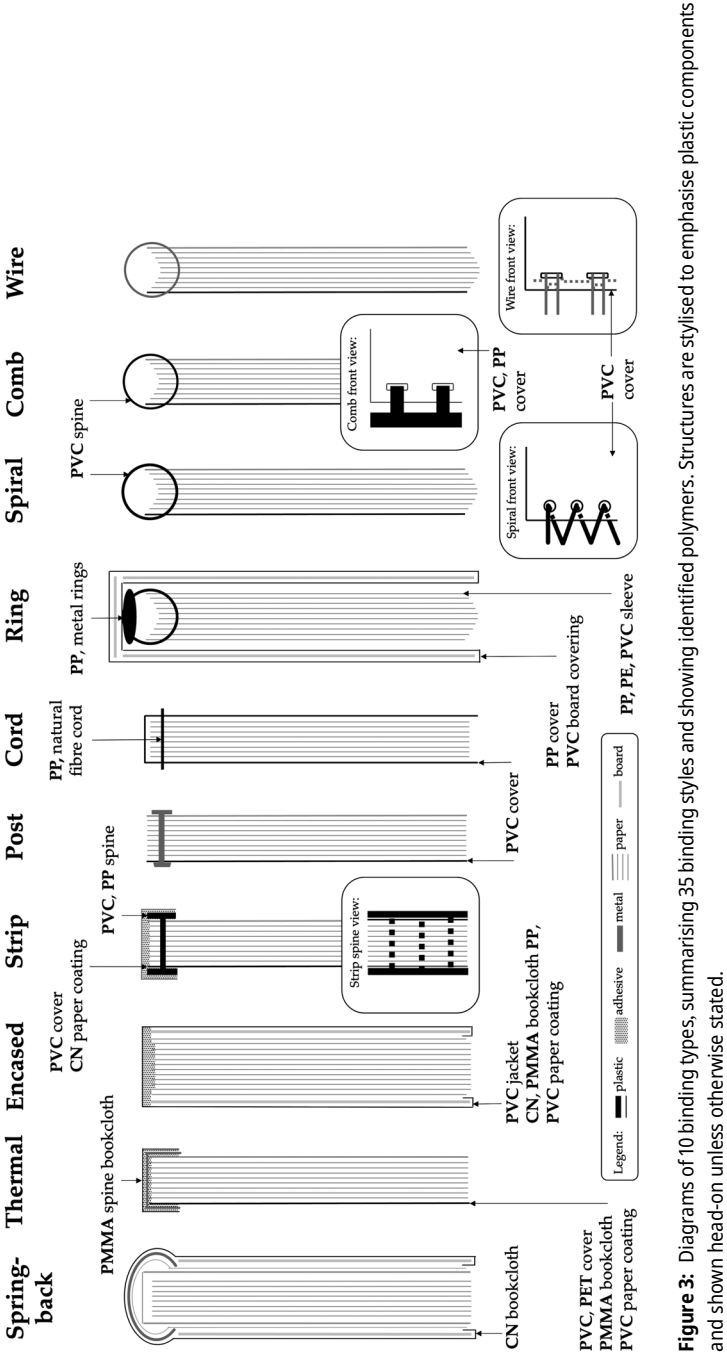
*Strip bindings* (2.0%) found in the collections had PVC and PP spines with straight prongs, and front covers of CN-coated paper or clear PVC. Strip bindings sometimes had spine coverings with natural fibre book cloth, making them visually alike thermal bindings until the cast plastic spine was identified.

*Cord bindings* (1.3%) were visually distinct, tied with PVC or natural fibre tied cords passed through punched holes. Some cords were threaded through the text-block only, with covers attached at a hole-punched guard, while others were directly passed through holes in PVC covers.

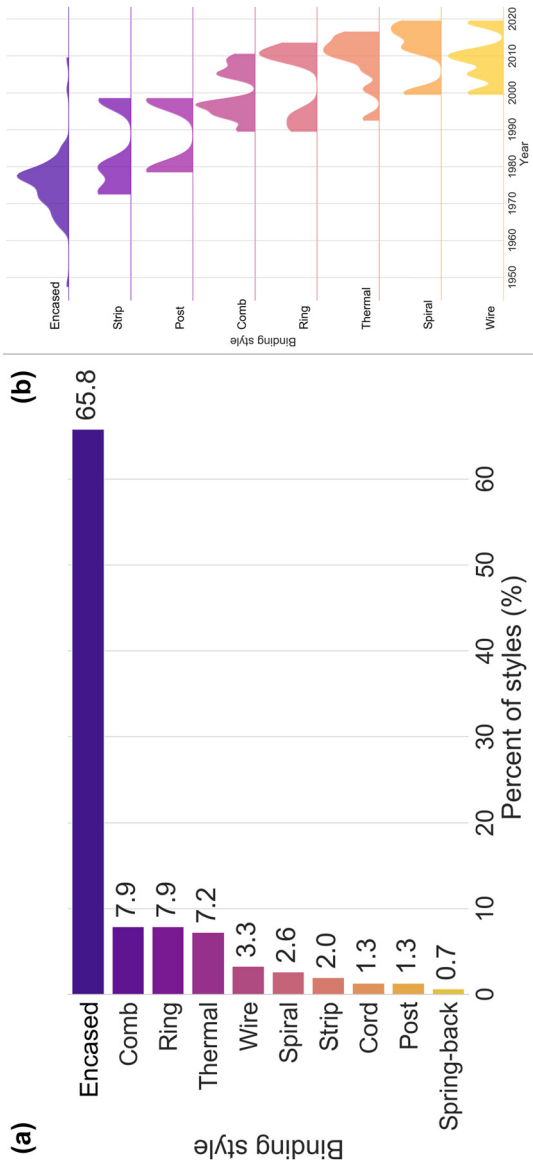
*Post bindings* (1.3%) in the collections all had metal split or screw posts, with PVC covers over the posts rather than bound in.

Lastly, the single *spring-back binding* with plastic components had a CN-coated book cloth cover (0.7%).

When plotted by year of production (Figure 4b), changes in the usage periods of binding styles can be seen. Encased bindings have the greatest range in production years 1949–2001, peaking in the late 1970s. This long period of evidenced usage may be explained by the larger number of books surveyed in this style, and the fact that these styles have a longer documented history. Although comb and ring bindings are the second-most common styles, the periods of usage span just over two decades,



**Figure 3:** Diagrams of 10 binding types, summarising 35 binding styles and showing identified polymers. Structures are stylised to emphasise plastic components and shown head-on unless otherwise stated.



**Figure 4:** (a) Frequency of binding styles found in 152 books. (b) Distribution of binding styles by year of production if known, showing 125 items. Cord and spring-back bindings could not be shown on the plot because each had only 1 dated instance in 1963 and 1991 respectively.

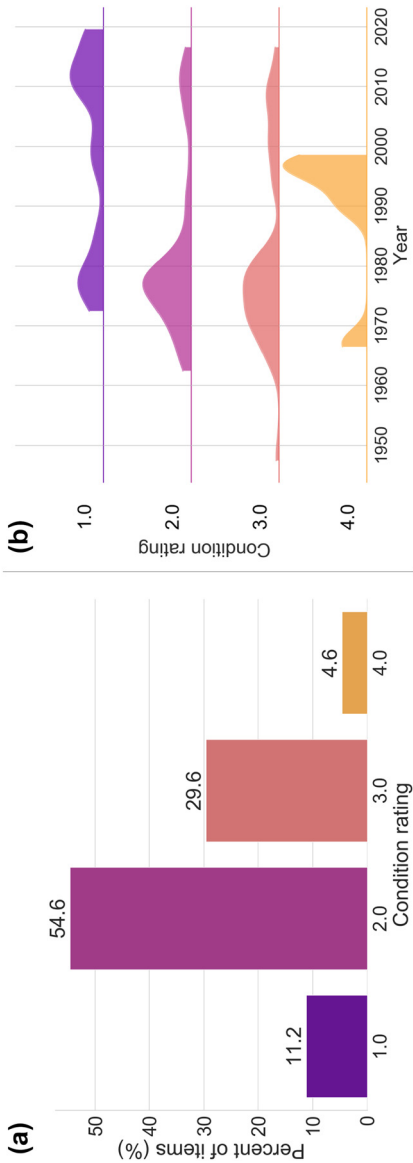
with no examples before 1990. Strip and post bindings appear to have waned in popularity, with no examples after 2000, while thermal and spiral bindings appear to be gaining in popularity since the mid-2000s. Note that 16.4% of the collection had no identifiable year of production.

### 3.3 Condition and Damage

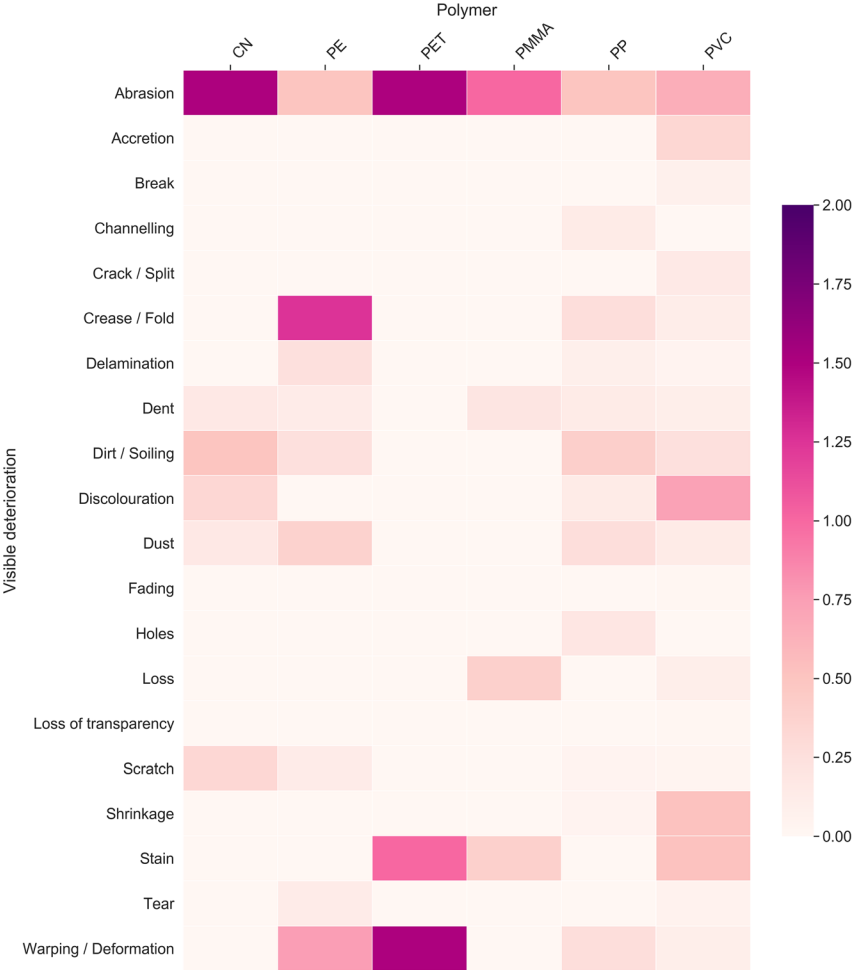
When the 152 items were rated on a scale of 1–4, the average overall condition rating was 2.28. A distribution plot of the condition ratings shows that most of the items had a rating of 2 (54.6%), indicating perceptible and moderate deterioration (Figure 5a). 29.6 and 4.6% had a rating of 3 and 4 respectively, suggesting that approximately a third of the surveyed collections would likely require conservation attention before access or display. These percentages are similar to the condition levels found in the POPART surveys, in which 13, 55, 25, and 7% were rated at level 1, 2, 3, and 4 respectively, and the overall average was 2.26 (Keneghan et al. 2012, 134). Overall results suggest that the condition of plastics in the surveyed book collections is comparable to that of plastics in museums.

The distribution of condition rating over time can be seen when plotted by year of production (Figure 5b). Condition rating does not appear to be linearly associated with the age of the item, as there is no clear pattern observed in the peaks of the plots. Items with a condition rating of 4 have a bimodal distribution, with a dip appearing in the 1980s. This non-normal distribution may be explained by a survivorship bias in the sampling process (Walters 2021, 4). Possibly, items in poor and unacceptable condition are preferentially not collected or discarded, and therefore do not appear in the sample. Alternatively, changes in additives and manufacturing processes, such as the phasing out of phthalate plasticisers due to health risks (Czogala, Pankalla, and Turczyn 2021; Mathieu-Denoncourt et al. 2015; Waentig 2008, 244), may have impacted trends in condition, but the analysis of plasticisers is beyond the scope of the current study. Future studies with larger sampling sizes and focused study of formulation changes may confirm factors impacting condition.

Similarly, condition rating does not appear to be correlated with polymer type. Components were ranked on a scale of 0–4 for each of 20 visible deterioration types, where 4 is important and general degradation. When shown on a heat map by polymer type (Figure 6), there is a row of dark and medium-dark cells across the abrasion deterioration type, but no such trend appears for other deterioration types or polymers. Outside of abrasion, the darkest cells appear at warping or deformation for PET, creasing or folding for PE, and staining for PET. Once again, a sampling bias may be present, as the sample sizes of most polymers in the collection were small. PVC appears to have a higher number of medium-dark cells, but despite the large sample size, does not have the highest average deterioration levels.



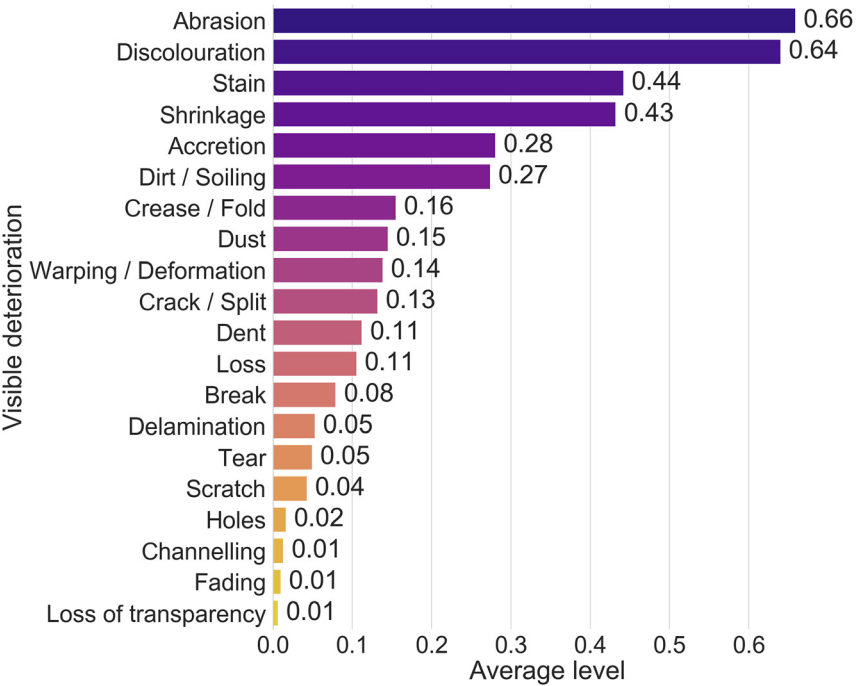
**Figure 5:** (a) Distribution of condition ratings of 152 items. (b) Distribution of condition ratings by year of production if known, showing 125 items. Ranked on a scale of 1–4, where 1 is slight and limited degradation, and 4 is important and general degradation.



**Figure 6:** Heat map showing average deterioration level for each type of visible deterioration by known polymer, 296 components shown. Ranked on a scale of 0–4, where 4 is important and general degradation.

Condition rating could not be meaningfully compared with storage environment, as there was only partial documentation of the environmental conditions for the collections surveyed.

A comparison of the average condition rating of the 20 visible deterioration types shows that some had higher average levels compared to others (Figure 7). For example, abrasion ( $0.66 \pm 0.85$ ) and discolouration ( $0.64 \pm 1.09$ ) had the highest



**Figure 7:** Average condition levels for each type of visible deterioration in 303 components. Ranked on a scale of 0–4, where 4 is important and general degradation.

average ratings and affected more components compared to fading ( $0.01 \pm 0.17$ ) and loss of transparency ( $0.01 \pm 0.08$ ). To consolidate the likely factors contributing to deterioration, types of visible deterioration were grouped under four damage categories and ranked on the item level (see Appendix Table A2): physical forces ( $1.50 \pm 1.01$ ), added material ( $1.39 \pm 0.96$ ), inherent instability ( $1.33 \pm 1.23$ ), and exposure to ultraviolet (UV) radiation ( $0.42 \pm 0.98$ ). As there are overlaps in the possible contributing factors for damage types, categories were assigned based on the most common hypothesised cause. Damage categories allowed for the formulation of recommendations (see Section 4).

## 4 Discussion

### 4.1 Implications of Identified Polymers

The six identified plastic polymers are considered common in cultural collections. A comparison with the collection surveys at NYUL and NLCR shows similarities in

**Table 4:** Comparison of plastic polymers identified in surveys of library and archive materials (∇ = book collections; \* = mixed archive).

| Survey                          | National Library of the Czech Republic (Vávrová et al. 2021) | New York University Libraries (Stein, Pace, and McCann 2021) | Australian paper-based collections |
|---------------------------------|--------------------------------------------------------------|--------------------------------------------------------------|------------------------------------|
| No. of items                    | > 500                                                        | 138                                                          | 165 (*236)                         |
| No. of polymers                 | 6                                                            | 12                                                           | 6 (*10)                            |
| Polymers found                  | –                                                            | –                                                            | –                                  |
| Acrylonitrile butadiene styrene | –                                                            | *                                                            | –                                  |
| Cellulose acetate               | ∇                                                            | *                                                            | *                                  |
| Cellulose nitrate               | ∇                                                            | *                                                            | ∇                                  |
| Polyamide                       | –                                                            | –                                                            | *                                  |
| Polycarbonate                   | –                                                            | –                                                            | *                                  |
| Polyethylene                    | ∇                                                            | *                                                            | ∇                                  |
| Poly(ethylene terephthalate)    | –                                                            | *                                                            | ∇                                  |
| Poly(methyl methacrylate)       | ∇                                                            | *                                                            | ∇                                  |
| Polypropylene                   | –                                                            | *                                                            | ∇                                  |
| Polystyrene                     | –                                                            | *                                                            | *                                  |
| Polyurethane                    | ∇                                                            | *                                                            | –                                  |
| Poly(vinyl acetate)             | –                                                            | *                                                            | –                                  |
| Poly(vinyl chloride)            | ∇                                                            | *                                                            | ∇                                  |
| Urea formaldehyde               | –                                                            | *                                                            | –                                  |

identified polymer types (Table 4). More types of polymers can be seen in the mixed collections compared to book-only collections, which can be explained by the greater variety of function and formats in records and ephemera. 14 polymers are identified across the surveys, indicating a tendency towards using the same pool of materials for mass-produced books and records.

Polymers common to all three discussed surveys are CN, CA, PVC, PE, and PMMA. It can be inferred that there is a high likelihood of the presence of malignant polymers in libraries and archives. This outcome aligns with the questionnaire of Australian archives, indicating the presence of malignant plastics in 41–70% of responding institutions (Chu and Nel 2023, 7).

Based on existing plastics conservation guides, malignant polymer types should be given greater priority in collection care (Fenn and Williams 2018; Shashoua 2008). However, in the present survey results for book collections, there was no association observed between polymer type and the degradation level of components. Lack of association between polymer type and condition is likely explained by:

- The difference in collection type, since different plastic forms are found in books compared to archives or museums. CN was only present in book cloth additives,

rather than the film form more commonly associated with rapid degradation. Further investigation into the deterioration of coated textiles and papers may be needed to understand how physical form affects deterioration in the same polymer.

- The small sample sizes of the polymers, other than PVC, resulting in sampling error. PET, considered a stable plastic, had the highest average degradation level. Although PVC displayed the greatest variety in visible degradation, this may also be explained by the significantly greater number of PVC samples. More comprehensive datasets may reveal different results.

A limitation of the present survey is that adhesives, plastic additives, and encapsulated foams were not identified. This was due to the need for performing only non-invasive analysis in a short timeframe. Additionally, some components could not achieve a good contact with the ATR window and could not be identified with FTIR. Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) may be used in future surveys that allow destructive sampling to enable the identification of both polymers and additives (Lavédrine, Fournier, and Martin 2012, 105). Although adhesives were descriptively noted when documenting binding structures, sampling of the adhesives would provide additional information on degradation patterns, such as adhesive failure in encased bindings. Previous comparative studies of the strength of book adhesives have been performed and may also be consulted for examples of adhesive types (Pasanec Preprotić et al. 2015; Petković, Pasanec Preprotić, and Vukoje 2018).

## 4.2 Implications of Identified Binding Styles

Most binding styles identified in this survey are assembled by adhesives or mechanical means applied on a loose-leaf textblock. This is in contrast to traditional binding styles that predominantly use sewing and adhesives on gathered pages (Johnson 1981, 153). As identified in previous literature on contemporary binding, commercial styles in Australia have grown to favour efficient and low-cost production suited for printing small editions of books (Chu and Knight 2023). Printing on loose sheets eliminates the need for laying out a book before the printing stage, increasing the speed of the book production process. These efficient binding styles are suited to the manuscripts and stationery bindings that were the focus of this survey, in contrast to books intended for mass publication.

Diagrams and descriptions of binding structures and polymers provided in the results section may assist collection care professionals in the identification of plastic

polymers in books from similar time periods (Figure 3 and Table 3). As many of the spine and cover components are mass-produced, it is possible that the same plastics are found in similar binding styles. As mentioned earlier, Australia often imports books and bookbinding materials, so the binding styles identified may not be limited to collections in Australia. For example, a large commercial retailer in Australia currently sells office binding materials made in China, Vietnam, and Portugal by companies based in the USA (Officeworks 2023). Ready-made book spines and covers like those identified in this survey are currently sold internationally, such as by retailers based in the USA, UK, Germany, and Singapore (Popular Office Solutions 2023; Presco UK Ltd 2023; Schmedt GmbH 2023; Staples 2023). The collection at AGNSW is known to be manufactured in China.

Whether the identified styles and materials reflect a global trend since the 1950s is beyond the scope of the current project but could be focus of future research. Further work may also address additional known commercial binding components such as sliding plastic spines, plastic screw-posts, and PUR imitation leather covers that were absent from the surveyed collections. Surveys of books from pre-1950s would create a more comprehensive picture of plastics in book-binding history.

### 4.3 Implications of Condition and Damage

Condition ratings indicate that books containing plastic have a comparable condition average to plastics in museum collections. About a third of these collections are likely to require conservation attention before access or display. However, unlike the museum surveys of POPART (Lavédrine, Fournier, and Martin 2012), no polymer types were identified as particularly unstable.

Instead of considering degradation by polymer type, types of visible degradation were divided into four categories by theorised cause. Preventive care is currently the most effective tool for prolonging the lifespan of plastic materials (Rychlý and Rychlá 2012, 211), so appropriate storage and access environments are described here to address the four damage types. Recommendations provided are tailored towards use in book collections, drawing on both existing conservation practices and available literature. Many strategies proposed are already common practice in collections, showing that some existing approaches can be readily adapted for the care of plastics.

*Physical forces* had the highest average deterioration level and is observed in all binding styles. This category of damage includes visible deterioration such as abrasion, creasing, denting, tears, and losses. Notably, abrasion is the only type of visible deterioration observed in all polymers. Damage from physical forces may be addressed through improved storage and handling measures. When stored on a

shelf, supports such as book ends and phase boxes decrease the chances of dents and deformation. Abrasion from shelf retrieval may be reduced with protective layers such as spacers between neighbouring books with protruding spines. Minimising handling, and handling with care on smooth, supported surfaces, can additionally reduce scratches and sudden impacts.

*Added material* includes stains, soiling, and mould deposits. As with physical forces, appropriate storage conditions with housing can reduce the introduction of contaminants that can damage heritage materials. Physical housing prevents non-original material such as dust from settling and adhering to plastic surfaces, in particular tacky surfaces resulting from plasticiser migration. Mould growth on plastics requires the presence of nutrients commonly found in organic soiling materials, such as oils, proteins, or plasticisers, in the presence of an elevated relative humidity (Fenn and Williams 2018). Therefore, appropriate environmental control can reduce mould growth, such as reducing humidity fluctuations in line with the local climate conditions (Pagliarino 2018). Handling with clean hands and surfaces can also reduce contaminant transfer.

*Inherent instability*, also termed inherent vice, describes rapid chemical and physical changes that can only be prevented with relatively drastic intervention. In this survey, shrinkage, delamination, and channelling were attributed to inherent instability, but the potential for such damage is exacerbated by environmental factors. For book collections, separation of malignant plastic components may be undertaken following a significance and risk assessment. Removing shrinking plastics, or those that exacerbate media transfer through solubility of media in plasticiser, may prevent further damage to valuable book components such as inscriptions, media and photographs while reducing physical damage to the structure of the book itself. In cases where separation is not deemed suitable, conservators may consider the use of low ventilation housing to reduce plasticizer migration and shrinkage.

PVC-P is a known malignant plastic and was particularly pervasive in the surveyed books. A major risk to PVC-P is plasticiser migration, which is best countered with containment to reduce ventilation. However, the type of material used for housing PVC-P requires close consideration. Commonly used materials in archives and paper conservation to protect against dust and soiling, such as tissue paper, have been shown to have a neutral to negative impact on plasticiser migration when in contact with PVC-P (Chu et al. 2022). Wrapping in PE has similarly been reported to have a negative impact by increasing plasticiser migration (Royaux et al. 2020, 139; Shashoua 2003, 35; 2008, 201). Mylar®, PET sheets that are commonly used in conservation, has been recommended as an enclosure for PVC-P to protect against soiling and plasticiser migration with the enclosure resulting in an equilibrium

between the environment and PVC-P (Shashoua 2003). However, other studies have reported that Mylar® in contact with PVC-P may cause discolouration (Royaux et al. 2020), or a blotchy surface haze (Chu et al. 2022). Appropriate storage materials for PVC-P are still under investigation.

*UV exposure* effects included fading and discolouration, although the latter is also impacted by inherent chemical instability. Reduction of UV exposure for all plastic types can be achieved through enclosed housing and using as low as practicable light intensity (lux) with reduced or absent UV radiation for display. All plastics identified in the Australian survey, excepting PMMA, are of medium to high sensitivity to sunlight and UV (Fenn and Williams 2018), indicating that low light and UV exposure can be implemented as a general preventive strategy within book collections containing plastics.

## 5 Conclusion

152 books containing plastic were surveyed in three Australian collections dating from the post-1950s. Of the six identified polymers, all readily identified with ATR-FTIR, PVC was found to be particularly pervasive. Observed binding styles were summarised into 10 binding types, for which structures and polymers are described to aid in non-invasive identification. Visible deterioration in the plastic components were documented and compared. Books containing plastic were most severely affected by physical forces when compared between four damage categories. Recommendations for storage environments and housing are provided to aid in the care of these books.

Results show that books containing plastic, as with any material type, require specialised conservation knowledge. As there is limited literature on plastics in bookbinding, this paper is positioned to aid caretakers of book collections in the care of increasingly common plastic components. While results are particularly relevant to Australian collections containing manuscripts and stationery bindings, the globalised nature of bookbinding suppliers suggests that similar materials may be found in collections with similar book styles. Results contrast and complement the historical conservation focus on plastics in museum objects, supporting the need for future research addressing the changing needs of paper-based collections.

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**Author contributions:** CC: project conception and methodology; data acquisition and interpretation; manuscript writing and editing; MB: data acquisition, manuscript writing and editing; SB: data acquisition, manuscript editing; FZ: data acquisition, manuscript editing; PN: academic supervision, manuscript editing.

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## Appendix

**Table A1:** Controlled vocabulary for data collection template, adapted for book materials from template developed for the PolyMuse project (Bell et al. 2022).

| Entity    | Fields                       | Description of values                                                                       |
|-----------|------------------------------|---------------------------------------------------------------------------------------------|
| Object    | Object name                  | Provided by organisation if available, otherwise given ‘Year-Creator-Number’                |
|           | Organisation                 | Organisation name                                                                           |
|           | Object type                  | Broad category of bound item, e.g., notebook, thesis                                        |
|           | Object summary               | Free text description of object                                                             |
|           | Object creator               | Author, owner and/or manufacturer if known                                                  |
|           | Year made                    | Earliest from year of binding or manufacture if known                                       |
|           | Binding type                 | 1 of 10 binding types (see Table 3)                                                         |
|           | Binding subtype              | Specific binding features within type                                                       |
|           | Associated materials         | Non-plastic materials stored with item                                                      |
|           | Inscriptions                 | Transcription of textual markings found on object besides primary text, such as brand names |
| Component | Number of plastic components | Whole number count of plastic features                                                      |
|           | Plastic identification       | Polymer full name or ‘unknown’                                                              |
|           | Plastic feature              | Description of plastic component in object, e.g., ‘spine’                                   |
|           | Plastic ID method            | Identification method, selected from: ATR-FTIR, inscription, or visual examination          |
|           | Plastic form                 | Selected from: cast, fibre, film, foam, or sheet                                            |
|           | Plastic firmness             | Selected from: soft (foams) or hard (all others)                                            |
|           | Plastic rigidity             | Selected from: rigid or flexible                                                            |
|           | Plastic opacity              | Selected from: opaque, translucent, or transparent                                          |
|           | Plastic colour               | Name of observed colour, e.g., ‘black’                                                      |
|           | Plastic texture              | Selected from: smooth or textured                                                           |

Table A1: (continued)

| Entity    | Fields              | Description of values                                       |
|-----------|---------------------|-------------------------------------------------------------|
| Condition | Date of report      | DD-MM-YYYY                                                  |
|           | Condition summary   | Free text description of condition                          |
|           | Visible degradation | Described on component level (see Table A2)                 |
|           | Degradation level   | Described for each visible degradation value. Integer 1–4   |
|           | Plastic feel        | Only noted if tackiness is present                          |
|           | Plastic smell       | Only noted if significant scent is present, e.g., ‘vinegar’ |
|           | Overall rating      | Described on item level. Integer 1–4                        |

Table A2: Controlled vocabulary for visible degradation of plastics, adapted for book materials from terminology list developed for the PolyMuse project (Bell et al. 2022).

| Category        | Visible degradation               | Definition                                                              |
|-----------------|-----------------------------------|-------------------------------------------------------------------------|
| Physical forces | Abrasion                          | Loss of surface material from contact, other than scratch               |
|                 | Break                             | Complete separation of material into smaller parts                      |
|                 | Crack/split <sup>a</sup>          | Clean line of partial separation extending from stress point            |
|                 | Crease/fold                       | Deformation line from tilting part of the material plane towards itself |
|                 | Dent                              | Depression of surface                                                   |
|                 | Holes                             | Perforation of material without loss                                    |
|                 | Loss                              | Missing area of material                                                |
|                 | Scratch                           | Concentrated loss of surface material from a narrow stroke              |
|                 | Tear                              | Deformed line of partial separation extending from stress point         |
|                 | Warping/Deformation <sup>a</sup>  | Change in planar shape of material, other than crease/fold              |
| UV              | Discolouration <sup>a</sup>       | Change in colour tone, other than stain                                 |
|                 | Fading                            | Loss of colour intensity                                                |
| Added material  | Accretion                         | Raised mass of non-original material attached to surface                |
|                 | Dirt/soiling                      | Non-original material embedded into surface                             |
|                 | Dust                              | Loose non-original particulate material on surface                      |
|                 | Stain                             | Localised discolouration from non-original material                     |
| Inherent vice   | Channelling <sup>a</sup>          | Lines of separation between layers                                      |
|                 | Delamination <sup>a</sup>         | Separation of layers, other than channelling                            |
|                 | Loss of transparency <sup>a</sup> | Increase in opacity                                                     |
|                 | Shrinkage <sup>a</sup>            | Reduction in dimensions of material                                     |

<sup>a</sup>Some types of degradation can be caused by multiple factors (e.g., crack/split may be from physical forces and/or inherent instability), so the category most relevant to the majority of the observed damage was selected.

**Table A3:** Examples of IR spectra for 10 identified plastic polymers, including extended SAM results, with assigned characteristic bands (Derrick, Stulik, and Landry 1999, 191–93; Stuart 2004).

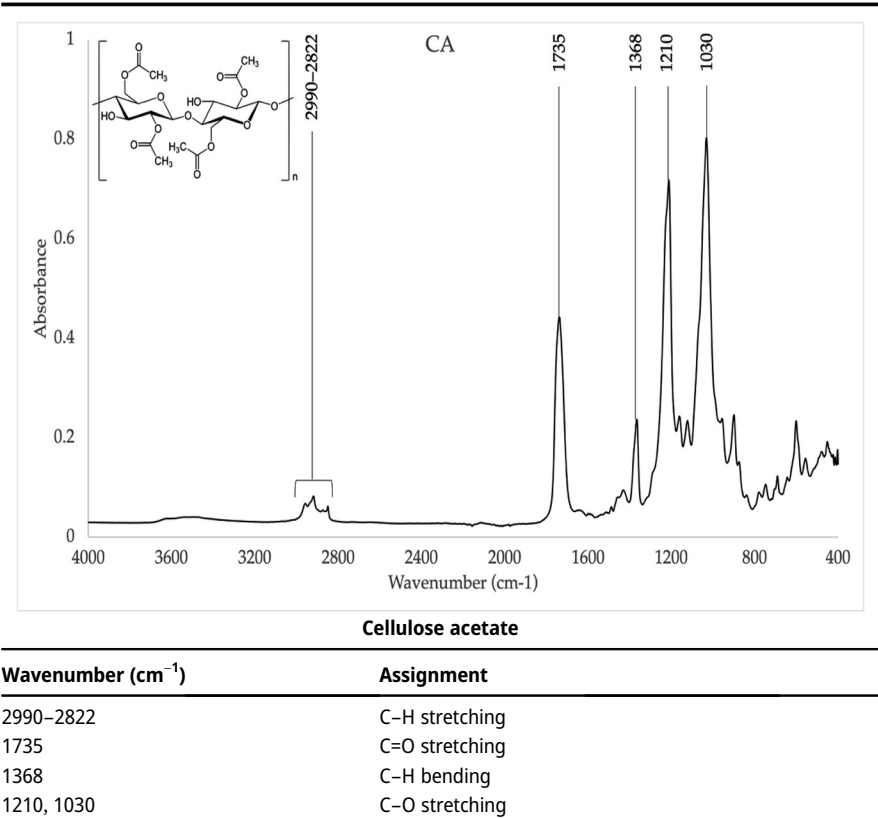
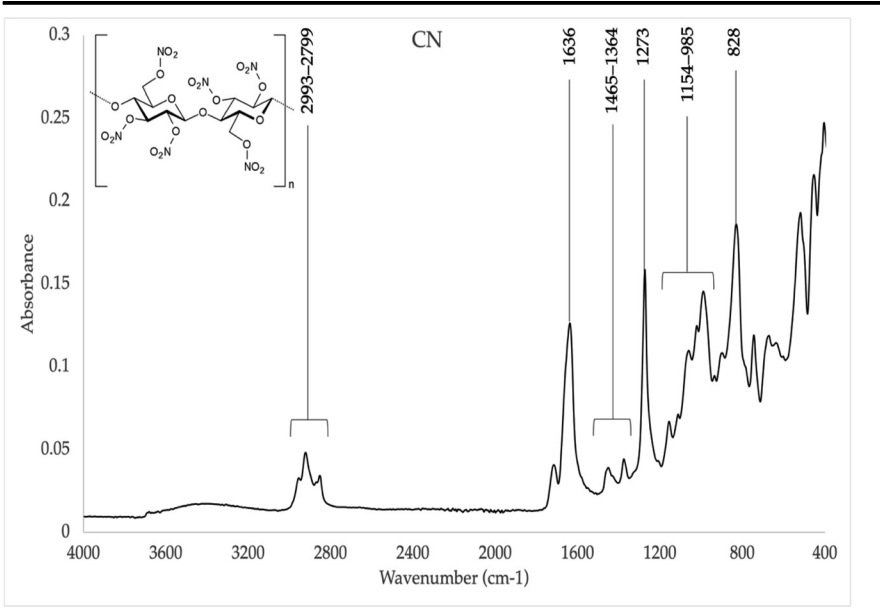


Table A3: (continued)



Cellulose nitrate

| Wavenumber (cm <sup>-1</sup> ) | Assignment     |
|--------------------------------|----------------|
| 2993-2799                      | C-H stretching |
| 1636                           | N-O stretching |
| 1465-1364                      | C-H bending    |
| 1273                           | N-O stretching |
| 1154-985                       | C-O bending    |
| 828                            | N-O bending    |

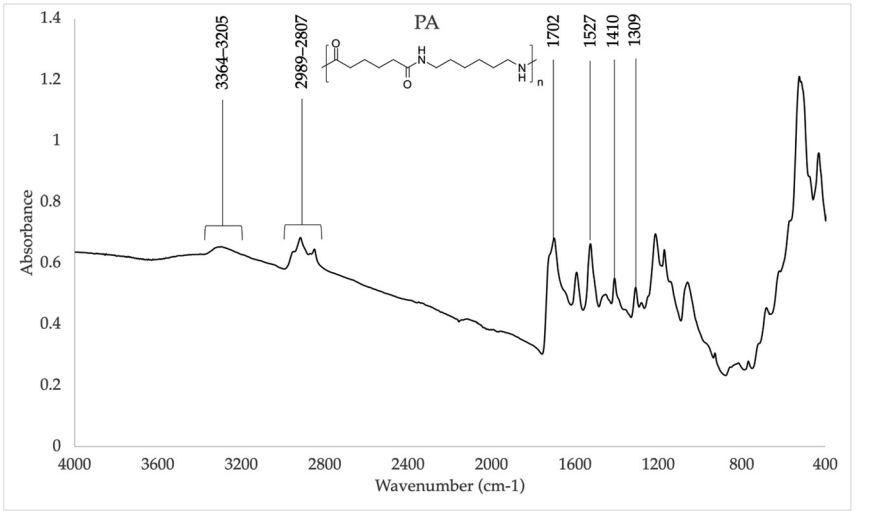


Table A3: (continued)

| Polyamide (Nylon 6,6)          |                |
|--------------------------------|----------------|
| Wavenumber (cm <sup>-1</sup> ) | Assignment     |
| 3364–3205                      | N–H stretching |
| 2989–2807                      | C–H stretching |
| 1702                           | C=O stretching |
| 1527                           | N–H bending    |
| 1410, 1309                     | C–H bending    |

| Polycarbonate                  |                         |
|--------------------------------|-------------------------|
| Wavenumber (cm <sup>-1</sup> ) | Assignment              |
| 3088–2838                      | C–H stretching          |
| 1768                           | C=O stretching          |
| 1591, 1502                     | Aromatic C–C stretching |
| 1218, 1187, 1158               | C–O stretching          |
| 1080, 1012                     | C–H bending             |
| 824, 762                       | Aromatic C–H bending    |

PC

3088–2838

1768

1591

1502

1218

1186

1158

1080

1012

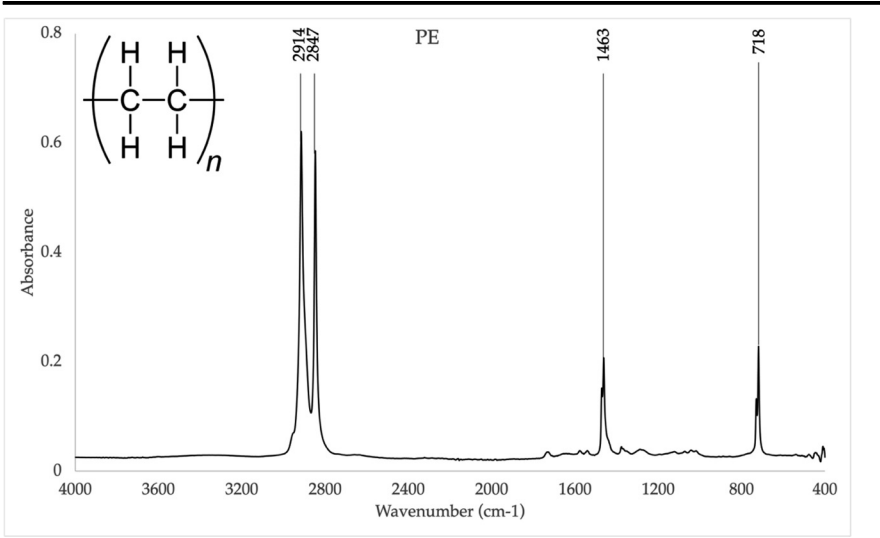
824

762

Absorbance

Wavenumber (cm<sup>-1</sup>)

Table A3: (continued)



Polyethylene

| Wavenumber (cm <sup>-1</sup> ) | Assignment     |
|--------------------------------|----------------|
| 2914, 2847                     | C-H stretching |
| 1463, 718                      | C-H bending    |

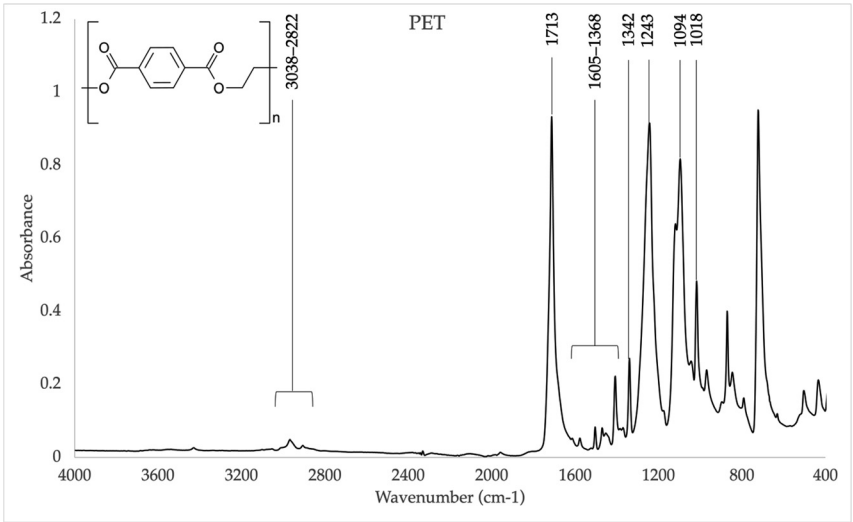


Table A3: (continued)

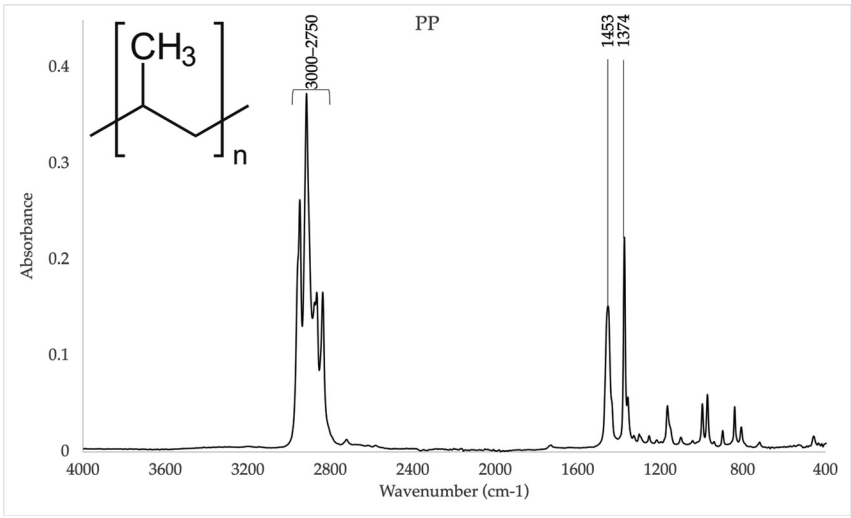
| Poly(ethylene terephthalate)   |                         |
|--------------------------------|-------------------------|
| Wavenumber (cm <sup>-1</sup> ) | Assignment              |
| 3038–2822                      | C–H stretching          |
| 1713                           | C=O stretching          |
| 1605–1368                      | Aromatic C=C stretching |
| 1342                           | C–H bending             |
| 1243, 1094, 1018               | C–O stretching          |

| Poly(methyl methacrylate)      |                           |
|--------------------------------|---------------------------|
| Wavenumber (cm <sup>-1</sup> ) | Assignment                |
| 3048–2809                      | C–H stretching            |
| 1723                           | C=O stretching            |
| 1465–1335                      | C–H bending               |
| 1238                           | C–C–O stretching          |
| 1191                           | C–O–C bending             |
| 1146                           | C–H <sub>2</sub> bending  |
| 962                            | C–CH <sub>3</sub> bending |

The figure displays the infrared (IR) spectrum of Poly(methyl methacrylate) (PMMA). The x-axis represents the wavenumber in cm⁻¹, ranging from 4000 to 400. The y-axis represents absorbance, ranging from 0 to 0.5. The spectrum shows several characteristic absorption bands: a broad peak around 3000 cm⁻¹ (C-H stretching), a sharp peak at 1723 cm⁻¹ (C=O stretching), and multiple peaks in the fingerprint region between 1500 and 500 cm⁻¹. Specific peaks are labeled with their wavenumbers: 3048-2809, 1723, 1465-1335, 1238, 1191, 1146, and 962. A chemical structure of PMMA is shown in the top left corner of the plot area.

Table A3: (continued)



Polypropylene

| Wavenumber (cm <sup>-1</sup> ) | Assignment               |
|--------------------------------|--------------------------|
| 3000–2750                      | C–H stretching           |
| 1453, 1374                     | C–H <sub>3</sub> bending |

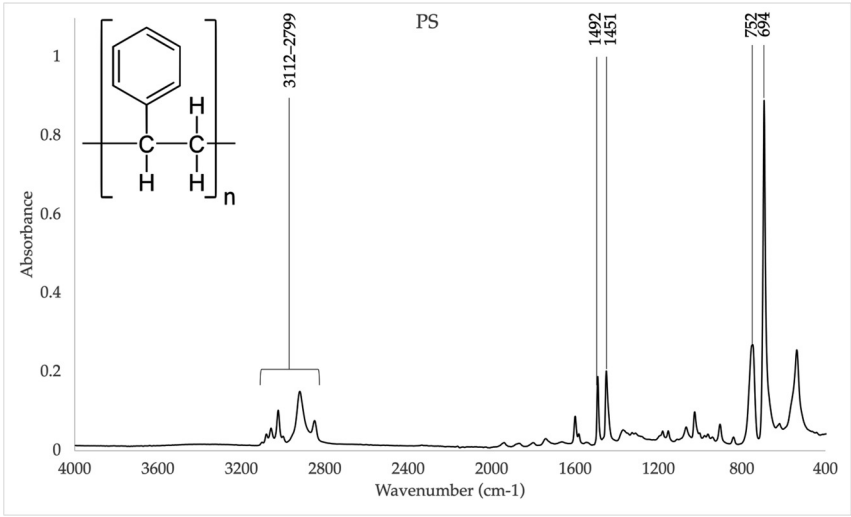


Table A3: (continued)

| Polystyrene                    |                         |  |
|--------------------------------|-------------------------|--|
| Wavenumber (cm <sup>-1</sup> ) | Assignment              |  |
| 3112–2799                      | C–H stretching          |  |
| 1492, 1451                     | Aromatic C–C stretching |  |
| 752, 694                       | Aromatic C–H bending    |  |

PVC + DEHP

3000–2810 1719 1600–1540 1460 1425 1256 1120 1072 693 609

Absorbance

Wavenumber (cm-1)

| Poly(vinyl chloride) plasticised with di-2-ethylhexyl phthalate |                 |          |
|-----------------------------------------------------------------|-----------------|----------|
| Wavenumber (cm <sup>-1</sup> )                                  | Assignment      | Compound |
| 3000–2810                                                       | C–H stretching  | DEHP     |
| 1719                                                            | C=O stretching  | DEHP     |
| 1600–1540                                                       | C=C stretching  | DEHP     |
| 1460                                                            | C–H bending     | DEHP     |
| 1425                                                            | C–H bending     | PVC      |
| 1256, 1120, 1072                                                | C–O stretching  | DEHP     |
| 693, 609                                                        | C–Cl stretching | PVC      |

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