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Blooming in polyurethane-coated fabrics: a literature review of a conservation challenge in collections

Blooming em tecidos revestidos com poliuretano: uma revisão da literatura sobre um desafio de conservação em coleções

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Abstract

This article presents a critical literature review on blooming in thermoplastic polyurethane (TPU)-coated fabrics. Blooming, typically described as whitish surface deposits, is a common deterioration phenomenon in TPUs in fashion and design collections. Drawing on polymer science, industrial sources, and heritage conservation studies, the review examines how blooming has been defined, investigated, and addressed in conservation practice. The literature identifies two recurrent mechanisms to explain blooming: additive migration as a physical process and hydrolysis as a chemical process. The latter, which is more commonly reported in heritage TPU artefacts, often results in the formation of adipic acid. Studies focusing on conservation remain extremely limited, with only a few case studies addressing cleaning and storage. The review highlights variability in terminology, proposed causes, and reported practices across the published literature. By synthesizing current knowledge and identifying key gaps, this article supports the development of interdisciplinary conservation strategies.

KEYWORDS
Plastics
Textiles
Whitish deposits
Fashion
Design
Adipic acid

Resumo

Este artigo apresenta uma revisão crítica da literatura sobre o *blooming* em tecidos revestidos com poliuretano termoplástico (TPU). O *blooming*, tipicamente descrito como depósitos esbranquiçados à superfície, constitui um fenómeno de deterioração comum em TPUs de coleções de moda e design. Com base em estudos da ciência dos polímeros, fontes industriais e investigação em conservação, analisa-se como o *blooming* tem sido definido, investigado e abordado na prática da conservação. A literatura identifica dois mecanismos recorrentes para o *blooming*: a migração de aditivos como processo físico, e a hidrólise como processo químico, frequentemente associada à formação de ácido adípico. Estudos centrados em conservação permanecem limitados, existindo poucos casos focados na limpeza e no acondicionamento. A revisão evidencia variabilidade na terminologia, nas causas e nas práticas de conservação descritas na literatura. Ao sintetizar o conhecimento atual e identificar as principais lacunas, esta revisão contribui para o desenvolvimento de estratégias interdisciplinares de conservação.

PALAVRAS-CHAVE
Plásticos
Têxteis
Depósitos esbranquiçados
Moda
Design
Ácido adípico

Introduction

Since the mid-twentieth century, synthetic polymers have played a central role in material culture, industry, fashion, design, and art [1-2]. Among them, polyurethanes stand out for their versatility, resulting from an adaptable chemistry based on diisocyanates, polyols, and chain extenders, which enables a wide range of mechanical and aesthetic properties and applications, from coatings and foams to elastomers and adhesives [3-5].

Thermoplastic polyurethanes (TPU) gained commercial relevance particularly from the 1960s onwards, since they offered a unique combination of functional performance and aesthetic versatility. TPUs offer elasticity, abrasion resistance, and durability, and can be manufactured as lightweight, waterproof, and breathable materials, enabling competition with traditional substrates such as leather [6-8]. In addition, TPU manufacturing allows for a wide range of surface finishes ranging from transparent to opaque, smooth to textured, highly glossy to matte, including metallic finishes. This combination of functional properties, aesthetic variability, and material accessibility supported their widespread application in fashion and design [5, 9-12].

The production of TPU-coated fabrics is inherently complex, involving multiple manufacturing and coating application processes, resulting in final products with varying layer thicknesses, morphologies, and surface aesthetics. In addition, these materials are composite systems, typically consisting of a fabric or leather substrate combined with one or more coating layers, in which the outermost layer (and in some cases additional ones) is composed of TPU. Fabric substrates may be woven, nonwoven, or knitted, and are mostly composed of cotton or polyester fibers. The coating layer(s) may have either compact or microporous morphologies, the latter including foam or coagulated structures. In the presence of more than one coating layer, intermediate layers can be added, for example, to enhance adhesion or provide a cushioning effect [13-14]. The various combinations of material composition and manufacturing processes of the entire coated fabric stratigraphy, particularly of the outermost TPU layer, may influence the long-term stability of the material [13-14].

Within the cultural heritage context, long-term deterioration issues, which were not initially apparent or even anticipated during production, become increasingly visible as the material ages. Numerous factors such as chemical formulation, aging time, environmental conditions, and even previous wear/use, might contribute to degradation, revealing their highly challenging nature.

One of the most common degradation phenomena in TPU-coated fabrics is blooming [6, 15], which appears as whitish deposits on the coating's surface (Figure 1), particularly in those formulated with aromatic diisocyanates and polyester polyols [16].

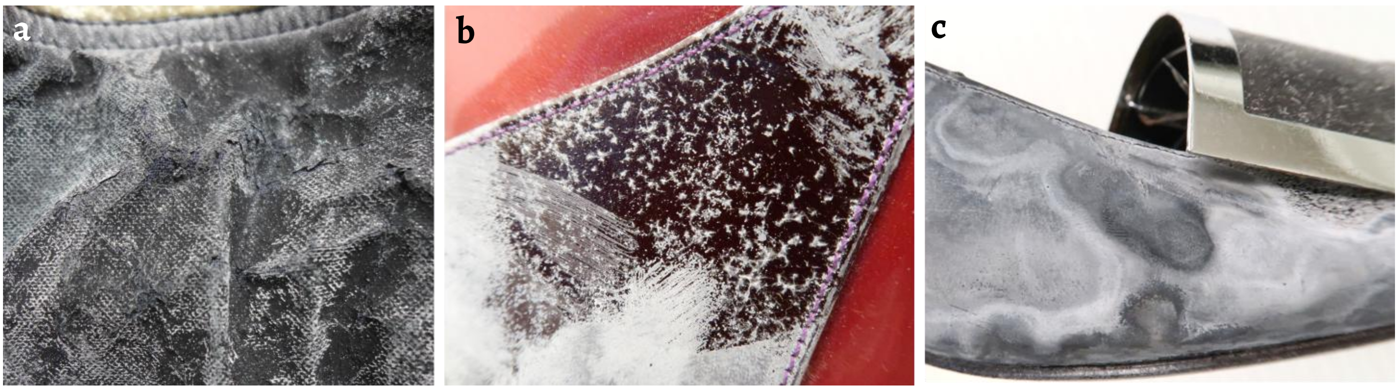

Figure 1. Details of blooming deposits on polyurethane-coated fabrics illustrating different visual manifestations of blooming: *a)* powder-like deposits; *b)* dense and dispersed deposits; *c)* haze-like deposits.

This damage can dramatically change the visual identity of the affected object, compromising the designer's intent and its exhibition value [17]. Although increasingly present in museum collections, TPU-coated fabrics have received limited scholarly attention, with only a small number of isolated conservation studies published over the past two decades [6, 16-23]. Therefore, blooming remains poorly understood, particularly in terms of its chemical variability, underlying causes and mechanisms, and the impact of conservation strategies intended to mitigate or reverse its effects, leaving conservators with limited reference tools.

This dispersed and limited knowledge on blooming in TPU highlighted the need for a more systematic and interdisciplinary investigation into the phenomenon. In response, the *InBloom* project (2025-2026) [24] aimed to tackle this knowledge gap. Given the growing number of affected objects reported in the literature and the limited consolidated information on this phenomenon, a comprehensive review of blooming in TPU-coated fabrics is presented.

Therefore, this work aims to synthesize interdisciplinary definitions of blooming in TPU and to examine the mechanisms proposed for its development, with particular attention to the role of coating formulations and additives from an industrial perspective. It brings together documented heritage case studies of TPU-coated fabrics exhibiting blooming, and critically compares the analytical approaches used to characterize both the coatings and the surface deposits. Given the limited number of studies available, selected case studies involving TPU elastomers are also considered, as their material similarity provides complementary insights. Finally, this research discusses reported preventive and active conservation strategies, with particular emphasis on cleaning approaches, and highlights key gaps in knowledge regarding their long-term effectiveness.

Methodology

This review is based on a structured critical analysis of the literature addressing blooming in TPU-coated fabrics, particularly on fashion and design case studies, and textile industry and polymer science literature. This study has been designed to compile existing knowledge, identify points of convergence, divergence, and limitations, as well as reveal how blooming has been defined, interpreted, and addressed across different disciplinary contexts, in order to support conservation decision-making.

Literature search strategy and study limitations

The literature search was conducted using physical library resources and online databases, including Web of Science, B-on, Google Scholar and Google Patents. The search was conducted in English using combinations of keywords related to the material, damage phenomena, and application context, including: thermoplastic polyurethane, TPU-coated fabric, polyurethane coating, blooming, adipic acid, efflorescence, surface deposit, whitish deposit, white crystals, hydrolysis, migration, fashion, design, and museum collections. Reference lists of relevant publications were also considered to identify additional sources not found through database searches.

Given the interdisciplinary nature of the topic and the limited number of peer-reviewed studies focused on fashion and design, additional sources, including conference proceedings, theses, technical reports, project documentation, and personal communications, were considered when presenting relevant data. These choices reflect the limitations of the study. Even so, the methodology used enables a critical synthesis of current knowledge and highlights significant research gaps

Results and discussion

Defining blooming in TPU across disciplines

This section does not seek to establish a single or normative definition of blooming, but rather to map how the term has been used and interpreted across different disciplinary, temporal, and material contexts.

The term blooming has been used in different ways across polymer science, industrial engineering, and heritage conservation, even in the context of TPU materials. Despite this variation, the fields still share overlapping views and complementary insights into the same phenomenon.

In engineering and polymer science, blooming is generally described as a migration phenomenon. Seah and Dasari (2025) [25] describe it as "the chemical migration phenomenon in which additives, pigments, and/or plasticizers in the polymer migrate to the surface as a result of phase separation (limited solubility) in the host polymer". The process is expressed in terms of kinetics driven by temperature and concentration gradients, and for additives, such as plasticizers, it involves their diffusion onto the material surface, followed by evaporation. Similarly, IUPAC (2004) [26] defines blooming as the "process in which one component of a polymer mixture, usually not a polymer, undergoes phase separation and migration to an external surface of the mixture". Wypych [27] further frames it as a solid-gas interface phenomenon resulting from the migration of stabilizers or plasticizers, which can, in severe cases, produce droplets due to incompatibility between the additive and the polymeric matrix.

In the coating and textile industries, blooming is considered an undesirable visual defect that compromises the appearance of TPU surfaces, often described as "surface haze" or "surface fogging" [28-29]. Patent literature [28-29] highlights this as a recurrent challenge, acknowledging the efforts to mitigate blooming appearance. Similar to the previous disciplines, it is identified as a consequence of the migration of low-molecular-weight species, such as cyclic polyester oligomers [30]. Technical data sheets for water-based TPU coating systems warn that incomplete water evaporation may cause "hazing/blooming", recommending the use of a retarder thinner to mitigate its appearance [31]. Fung [13] describes blooming as an unacceptable surface "discoloration effect", caused by additive migration, namely, ammonium stearate. Thus, industry defines blooming mainly by the mechanism that causes it, rather than through detailed morphological descriptions, framing it as a production or formulation issue.

On the other hand, in the heritage conservation field, definitions have historically emphasized the visual appearance of blooming, while also describing possible causes for its appearance in some cases. The *POPART* project (2012) [21] describes bloom as a "whitish deposit with crystalline aspect". Other early descriptions refer to "white crystals", "white degradation product" [32], "powdery deposit on the surface of objects (...) usually caused by the migration of additives" [33] or a "white or grey matte film covering surfaces", linked to the "migration of antioxidants to surfaces", particularly in synthetic rubbers [2]. Some of these definitions overlap with that of "chalking", defined as "white powder on surfaces", resulting from "separation of pigment or filler from polymer" [2], making the terminology ambiguous. França de Sá [20] also described blooming on TPU-coated garments as "white powder at the surface (chalking)", reflecting this overlapping in terminology.

In a more recent study, Krieg et al. [34] emphasized the potential for misdiagnosing blooming as mold, highlighting the importance of accurate identification. The authors also categorize previous descriptions of blooming into two distinct forms: crystalline and amorphous. The crystalline form is visible to the naked eye as a shiny efflorescence, usually white, caused by migrated additives or degradation products. In contrast, the amorphous form is not visibly crystalline, having a matte, waxy, and powdery whitish-grey appearance.

Within the context of the *Glossy Surfaces* project, blooming was described in relation to coated fabrics as the occurrence of "whitish surface deposits that can evolve to a more crystalline appearance over time" [6]. Multiple analytical studies have identified adipic acid in surface deposits, describing it as blooming, and have interpreted its presence as related to the chemical aging of polyester-based TPUs [6, 15, 17, 20, 35-36]. Its presence is related to the hydrolytic and thermal degradation of the polyester polyol in humid environments [37-38]. Polyester polyols are typically synthesized from adipic acid and diols such as ethylene glycol or 1,4-butanediol. The hydrolysis of the ester linkage causes the ester to revert to the precursor acid and alcohol raw compounds. Once formed, adipic acid further catalyzes hydrolysis by lowering the local pH (~2.7 in aqueous extracts), creating an autocatalytic process [4, 10, 17].

Although similar interpretations do not appear in polymer science or industry literature, to the best of the authors' knowledge, they were first articulated in a conservation context by van Oosten et al. [39]. Through artificial aging, it was demonstrated that polyester polyurethane foams hydrolyze into their basic components, decomposing them into adipic acid (and, under more extreme conditions, polyol fragments). Although adipic acid was widely identified in polyester-based polyurethane foams [20, 39-40], it does not appear as blooming on the surface because it remains trapped within the foam's porous structure. This contrast highlights the particular challenge of polyester-based TPU coatings, in which these deposits readily form on the surface.

The broad use of the term blooming in TPUs across disciplines, and sometimes overlapping with other terms, reflects two complementary but context-dependent explanatory models. In polymer science, engineering, and industry, blooming is typically described as the migration or phase separation of pre-existing low-molecular-weight compounds, an issue more related to relatively newly produced materials, which can be mitigated through formulation adjustments. On the other hand, in heritage conservation and degradation studies, blooming is mostly associated with the appearance of whitish deposits at the surface, and particularly in polyester-based TPU, related to its chemical aging and hydrolytic cleavage. These mechanisms may co-exist or occur sequentially, hindering diagnosis. The interdisciplinary comparison highlights how similar visual symptoms described as blooming have been interpreted through different explanatory frameworks, depending on disciplinary context and the material condition of the objects under study.

Industrial context: the influence of TPU formulation on blooming appearance

Nowadays, it is recognized that TPU chemistry, full coating formulation, and processing significantly prefigure the aging patterns observed in collections today [2]. Chemically, TPUs are synthesized from aromatic or aliphatic diisocyanates and mainly with polyester- or polyether-based polyols, extended with short-chain glycols or diamines. These raw materials, along with a broad range of additives, are blended into homogeneous coating pastes or resins that are uniformly applied to fabric or leather substrates [13, 41]. Coupling agents and adhesion promoters improve cohesion within the coating and at the polymer-textile interface, while plasticizers, stabilizers, pigments, and fillers fine-tune processability and appearance [13, 27, 42].

The selection of monomers, as well as additives added to the formulation, determines the mechanical properties and influences the long-term stability of the polymer [4, 11]. For instance, aromatic diisocyanates, such as toluene diisocyanate (TDI) and methylene diphenyl diisocyanate (MDI), offer superior strength and cost efficiency than aliphatic diisocyanates, but tend to yellow under light exposure. Multilayer constructions, combining aromatic intermediate layers with aliphatic top coatings (usually hexamethylene diisocyanate, HDI, or isophorone diisocyanate, IPDI) were introduced to enhance light stability at lower cost [4-5, 11]. Similarly, the polyol backbone determines hydrolytic resistance, as polyester-based TPUs are more prone to hydrolysis under humid conditions than polyether polyols, leading to the structural weakening of the polymer [5, 13]. Additives can also cause instability, as poorly matched low-molecular-weight components can migrate over time, leading to phase separation and surface alterations such as tackiness, sweating, haziness, or whitish efflorescence [9, 25, 27, 42-43].

In the assessed literature, the occurrence of blooming is not linked to the manufacturing methods used to produce TPU-coated fabrics, nor to the fabric or leather substrates or the existence of intermediate layers. Instead, and depending on the research field, blooming is consistently associated with one of two mechanisms: the migration of additives (physical process), in the case of textile and coating industries; or with hydrolysis-derived degradation products appearing on the materials' surface (chemical process), mainly in heritage conservation. In any case, both associated causes indicate that their origin lies in the raw materials and chemical composition of the TPU coating formulation.

Although TPUs are inherently flexible due to their segmented block structure, external plasticizers might be added, especially in fashion and design contexts, to modify processability and appearance [44-45]. For instance, Tomás Ferreira et al. [45] identified, for the first time, di(2-ethylhexyl) phthalate (DEHP) in three case studies composed of aromatic polyester-based TPU-coated fabrics. In these cases, DEHP was suggested to be present either as a contaminant, plasticizer in the TPU coating, or as a plasticizer from an intermediate layer, possibly a plasticized poly(vinyl chloride) (p-PVC). Polymer science handbooks have already discussed that plasticizers' permanence within the polymer matrix depends on their molecular weight, polarity, and compatibility with the host matrix [27, 44]. In addition, experimental studies show that diffusion and evaporation of plasticizers are influenced by temperature, plasticizer chemistry, the gas flow rate above the surface, and the volume of gas surrounding the material [43]. Even stabilizer or catalyst residues can contribute to polymer degradation in the long term [18].

Industry itself acknowledges the occurrence of blooming in TPU coatings used in coated fabrics, highlighting both the relevance and urgency of this issue. Technical reports and manufacturers' data sheets mention the possible appearance of whitish deposits or surface haze shortly after TPU production or during storage. In an industry site visit, Silva [46] shared a technical data sheet from TUBICOAT MP (CHT) – not publicly available – stating: "(…) es posible que se produzca un 'velo gris' en tiempos de almacenamiento prolongados sobre la superficie recubierta", meaning that a "grey haze" may develop on the coated surface after prolonged storage periods. The textile industry monitors this issue through fogging or emission tests [47], which measure volatile and condensable compounds in polymeric materials responsible for surface haze. Standards such as ISO 6452:2021, and equivalent ASTM or DIN procedures, are routinely used to assess the stability of coated fabrics, particularly in the automotive sector, underscoring industry-wide awareness of blooming-related phenomena [47].

Recent patents further frame blooming specifically in polyester-based TPUs, describing it as "surface haze" or "surface fogging" [28, 30] arising from the migration of low-molecular-weight species (notably cyclic polyester oligomers, by-products of polyol synthesis) [30] and propose compositional routes to suppress it. A series of patents by Farkas et al. describes TPUs in which the hydroxyl-terminated polyester intermediate is a poly(trimethylene adipate) glycol derived from 1,3-propylene glycol (or, optionally, from a bio-based 1,3-propylene glycol) and adipic acid [28]. In the examples described, these polyols, combined with a diisocyanate such as MDI, and a glycol chain-extender like 1,4-butanediol, remain largely blooming-free after four years of aging [29]. In contrast, comparable TPUs based on poly(tetramethylene adipate) glycol, derived from 1,4-butanediol adipate and produced under identical processing conditions, exhibited moderate to heavy blooming, which could be partially removed by simple rubbing of the surface [29]. Reduced levels of blooming can be achieved without the inclusion of monofunctional long-chain alcohols previously used to suppress blooming, relying solely on the specific polyester intermediate, standard chain-extender, and diisocyanate combination [28]. The European (EU) patent counterpart [48] also mentions the same low-bloom TPU architecture for the EU market. Overall, in these patents, the reduction of surface haze or blooming is achieved through compositional control by limiting the presence of migratable species.

Other recent patents, such as WO 2017/040505 A1 [30], address blooming in TPUs by identifying cyclic polyester oligomers, formed as by-products during polyester polyol synthesis, as the primary migratable species responsible for surface haze or visible bloom. The invention proposes the enzymatic treatment of polyester polyols with lipases or cutinases at moderate temperatures to selectively cleave these cyclic oligomers, thereby reducing their content in the final TPU material. Formulations prepared from polyester polyols with reduced cyclic oligomer levels exhibit a significantly diminished tendency to bloom [30].

Within this corpus of EU and U.S. patents, blooming is thus consistently attributed to the migration of pre-existing low-molecular-weight species. Overall, industrial patents emphasize compositional control and polyol design (polymer architecture, molecular weight, and cyclic oligomer content) as the main strategies for reducing the appearance of blooming. In contrast, heritage conservation-science studies, further addressed below, tend to associate blooming in TPU with the formation of acidic hydrolysis products, appearing as white efflorescence on the surface of aged TPU-coated fabrics, indicating that hydrolytic chain cleavage may act as an additional degradation pathway for blooming development.

Cultural heritage context: case studies on blooming in TPU-coated fabrics and rubbers

Within cultural heritage, most references published prior to 2020 generally mention blooming as a degradation phenomenon characterized by whitish deposits occurring in rubbers and plastics [2, 21, 33], with only three studies addressing it specifically in TPU-coated fabrics in fashion. Lavédrine et al. [21, 49] described a striking case from *La Valise des Nouveaux Réalistes* (1973) by Arman and other artists, in which a polyester-based TPU-coated fabric exhibited a thick white blooming. Pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) and Fourier transform infrared (FTIR) analysis of the deposits identified cyclopentanone and MDI derivatives, confirming blooming as degradation products of polyester-based TPU chains.

In 2014 and 2017, França de Sá and co-authors [20, 32] studied two historical garments by the designer André Courrèges from MUDE (Museu do Design, Portugal), both composed of aromatic and polyester-based polyols and presenting white powders/crystals on the surface. Although not explicitly described as blooming, the authors' descriptions align with the definitions outlined in the first section of this article [20, 32]. Moreover, infrared analysis identified these deposits as adipic acid, interpreted as a deterioration product from the polyester-based coating, and described as easily removable [20, 32]. In the 2017 study [20], outdoor aging experiments using model samples further confirmed this behavior: optical microscopy under reflected cross-polarized light revealed the formation of a whitish, removable layer only after three months of aging, which intensified after six months. These results resembled the degradation pattern observed in historical TPU-coated garments, particularly the formation of white surface powders. Despite these contributions, literature was limited to isolated cases and offered no broader understanding of blooming prevalence, formulation dependence, or behavior across collections.

This gap was addressed within the *Glossy Surfaces* project (2020-2023), the first large-scale investigation of TPU-coated items across multiple museum collections. Within the project, 66 TPU-coated artefacts from more than seven collections worldwide, covering the period from the 1960s to 2010s, were assessed through a multi-analytical approach. The artefacts included aliphatic polyester-based, aliphatic polyether-based, and aromatic polyester-based TPUs. The latter composition represented nearly 80 % of all TPU artefacts, dating from 1960s to 2010s, with many affected by blooming [16]. Moreover, adipic acid was detected in circa 90 % of the white deposits identified as blooming [17], regardless of the damage degree, and more present in aromatic polyester-based TPU [50-55]. Additional adipate-related compounds have been detected in a few cases as well [6, 16, 18].

Examples of case studies documented within the *Glossy Surfaces* project include three garments by Maria Gambina from the MUDE collection – a pair of black pants [6, 17], a black skirt (1998) [35], and an orange and pink jacket (1998/99) [6] – identified as aromatic polyester-based TPU-coated fabrics. Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) was used to identify the deposits, confirming the presence of adipic acid [6, 17, 35]. In the spectra of the TPU coating, a decrease in the intensity of the C=O band at c. 1727 cm^{-1}, along with spectral changes in the C–O–C region (c. 1200–1100 cm^{-1}), were detected, showing alterations consistent with ester bond cleavage. Moreover, the shift of the C=O band from 1727 to 1695 cm^{-1}, and the appearance of a shoulder at c. 1665 cm^{-1}, further indicated the formation of acidic species, supporting the hypothesis that blooming in polyester-based TPUs results from hydrolysis of the soft segment [16].

Other examples include a garment from MoMu (ModeMuseum, Belgium), an André Courrèges orange jacket (1970) [6], and three items from The Met (Metropolitan Museum of Art) Costume Institute´s collection, Diana Dew's *Electric Dress* (ca. 1967), a Golo Footwear Corporation boot (ca. 1970), and Rae Spencer-Cullen's *Hommage to Magritte* (ca. 1978) [36]. Another highly degraded red and black jacket, acquired as a research case study, was likewise characterized and an aromatic polyester-based TPU coating with adipic acid as blooming was identified [17].

Rodríguez Salinas and Ferrazza [8] conducted a comparative study of three pairs of shoes from the Kunstmuseum Den Haag (ca. 1970) by Charles Jourdan, Gucci, and Valentina [8]. All items featured polyester-based TPU coatings (mainly on leather substrates), showing blooming that transformed their original glossy "wet-look" finish into a matte, whitish surface. ATR-FTIR confirmed adipic acid as the crystalline efflorescence in the Charles Jourdan pair, a result highlighted by the authors, given the potential for misidentification as fatty acid spews from leather. This identification allowed possible treatment recommendations, such as caution when using polar solvents (e.g. ethanol or methanol) to remove the deposits, emphasizing the need to balance solubility with coating stability. The blooming of the other shoes was not identified.

Tomás Ferreira et al. [45] recently analyzed two additional case studies from the MUDE collection: a designer dress from 1999/2000 and a pair of designer trousers from 1998, both composed of aromatic polyester-based TPU. In line with previous studies, the blooming observed on the trousers was identified as adipic acid. By contrast, the blooming from the dress was tentatively identified as an adipate-based compound and, thus, associated with a possible migration process.

Regarding design collections, Bechthold [18] examined Joe Colombo's *Tube Chair* (1969) from Die Neue Sammlung, composed of an aromatic and aliphatic polyester-based TPU, with a higher aromatic content on the outer layers. At the time, the coating did not exhibit blooming but was severely degraded by extensive cracking, flaking, and peeling. To investigate suitable conservation strategies, polyester-based TPU model samples were artificially aged under several conditions. Although not explicitly described as blooming, these model samples developed crystalline surface efflorescence whose morphology and chemical identification closely resemble phenomena later reported as blooming in TPU materials, as demonstrated by the artificial aging experiments. Exposure to hydrochloric acid vapors (6 mol/L) resulted in the formation of a crystal-like efflorescence after seven days. After 18 days, these structures branched into leaf-like crystals (200-500 µm in length), and by day 32, larger sheet-like crystals (200-800 µm in diameter) were observed by scanning electron microscopy (SEM). This efflorescence was identified as adipic acid by X-ray diffraction (XRD). Alkali exposure in 28 % ammonia solution led, after 13 days, to highly branched cauliflower-like structures (c. 30 µm in length), while after 27 days, to star-shaped structures composed of thin rods (500 µm maximum diameter and 20 µm rod thickness). XRD analysis identified these structures as ammonium adipate [18]. Further work in 2006 reported the consolidation of the Die Neue Sammlung *Tube Chair* with an aqueous anionic polyurethane dispersion (Bayer Isovin V), a treatment conducted in 2002 [56]. While blooming was not documented in either the 2002 or 2006 studies, in 2023, Bechthold reported that blooming had specially appeared on non-consolidated areas since at least 2018, although no further analysis was conducted [57].

Even though this review focused primarily on blooming on TPU-coated fabrics, this discussion also considered examples from other polyurethane forms, such as rubbers. Owing to their shared chemical composition, case studies on polyurethane elastomers provide valuable comparative data. For instance, the *Cosmos* (1967) knee-length boots by Pierre Cardin (Victoria and Albert Museum) exhibited a thick white waxy layer on their polyester-based TPU heel tips [58]. FTIR identified dibutyl adipate and adipic acid as the blooming constituents [58]. Spring and Flexer [59] reported a similar damage in two additional footwear case studies: the soles of George Best's Adidas Milano boots (1976), and the soles of Pelé's Yasuda boots (1969). The first case displayed heavy white crystalline deposits identified as calcium sulphate dihydrate, while the second presented a hard, powdery white efflorescence identified as suberic acid, a compound used as a plasticizer or an alternative to adipic acid in the synthesis of polyester polyols. Similarly, Llamas-Pacheco [60] studied Gaizka Mendieta's Kelme *Milenia* boots (ca. 1999), a pair of soccer boots whose Phylon/TPU soles exhibited extensive whitish crystalline blooming, suggested by the author as being adipic acid or an adipate, although not confirmed through analyses.

Beyond the identification of blooming in design and fashion items, its presence in utilitarian objects has also been documented. Krieg et al. reported blooming in several historical industrial objects, namely in one polyester-based TPU pressure handle from a 1970s mining hammer, identifying the crystalline efflorescence as adipic acid [34].

Together, these diverse case studies, from fashion, design, footwear, and industrial objects, point to the widespread occurrence of blooming in TPU materials. Table 1 compiles documented cases of blooming identified in TPU-coated fabrics and rubber-based TPU objects within the cultural heritage context. It summarizes the type, name and provenance of each object, approximate production date, chemical nature of the TPU formulation and identified blooming compounds, analytical techniques used for their identification, and bibliographic sources. In total, 21 case studies were identified, of which 16 concern TPU-coated fabrics and 5 involve TPU-rubber-containing objects.

Across these studies, several consistent patterns emerge. Blooming is consistently associated with polyester-based TPUs, particularly those synthesized with aromatic diisocyanates (MDI or TDI), aligning with polymer-science literature describing the hydrolytic susceptibility of polyester soft segments [11]. Adipic acid is by far the most frequently identified white efflorescence in both coated fabrics [6, 17, 20, 35-36] and elastomeric items [34, 58]. In some studies, complementary or derivative species such as ammonium adipate, dibutyl adipate, or other dicarboxylic acids (e.g., suberic acid in specific footwear soles) were also reported [6, 18, 58-59]. Infrared spectroscopy, mainly ATR-FTIR, is the primary analytical technique for identifying both TPU coatings and blooming compounds [6, 17, 35-36, 45], complemented by Py-GC/MS for formulation identification (namely additives and degradation products) [6, 34, 36], XRD for crystallographic characterization [18], and SEM for morphology assessment [8, 18].

These findings highlight both the tendency of blooming manifestations across heritage TPU materials and the need for further systematic research. Although existing studies mainly identify adipic acid as white deposits, the literature remains limited to isolated case studies, lacks standardized methodologies for blooming identification (including high-resolution photographic and microscopic documentation), provides an incomplete characterization of TPU formulations, and rarely examines factors such as environmental and handling conditions throughout the TPU's lifespan that may influence blooming development.

Table 1. Summary of reported blooming identifications in TPU-coated fabrics and rubber objects according to the accessed literature.

TPU class	Object (date), author, institution	TPU formulation		Blooming		References
		Chemical composition	Analytical techniques*	Chemical composition	Analytical techniques*	
Coated fabrics	Flea market gloves (mock-up samples)	Polyester-based TPU	ATR-FTIR	Adipic acid (acid hydrolysis) and ammonium adipate (alkaline hydrolysis)	XRD	[18]
	La Valise des Nouveaux Réalistes (1973) by Arman and other artists	Polyester-based TPU	FTIR	Cyclopentanone and MDI derivatives	Py-GC/MS, FTIR	[49]
	Brown Dress (c.1970), André Courrèges, MUDE	Aromatic (MDI) polyester-based TPU	μ-FTIR	Adipic acid	μ-FTIR	[20]
	Blue Dress (c.1965), André Courrèges, MUDE					
	Blue Coat (c.1971), André Courrèges, MUDE	Aromatic polyester-based TPU				[20, 32]
	Electric Dress (ca. 1967), Diana Dew, CI	Aromatic (TDI) polyester-based TPU	ER-FTIR, μ-FTIR, Py-GC/MS		ER-FTIR, μ-ATR-FTIR	[36]
	Boot (ca. 1970), Golo Footwear Corporation, CI	Aromatic (MDI) polyester-based TPU				
	Hommage to Magritte (ca. 1978), Rae Spencer-Cullen, CI					
	Skirt (1998), Maria Gambina, MUDE	Aromatic polyester-based TPU	ATR-FTIR		ATR-FTIR	[35]
	Orange Jacket (1970), André Courrèges, MoMu		μ-ATR-FTIR		μ-ATR-FTIR	[6]
	Pants (1998), Maria Gambina, MUDE		ATR-FTIR		ATR-FTIR	[6, 17]
	Jacket (1998/99), Maria Gambina, MUDE					[6]
	Flea market degraded red and black jacket (purchased case study)					[17]
	Shoes, Charles Jourdan (ca.1970), Kunstmuseum Den Haag	Polyester-based TPU coating				[8]
	Shoes, Valentina, (ca.1970), Kunstmuseum Den Haag	Aromatic polyester-based TPU coating		Only visually identified	-	
	Shoes, Gucci, (ca.1970), Kunstmuseum Den Haag			Only visually identified	-	
Rubbers	*Cosmos* boots, Pierre Cardin (1967), V&A Museum	Polyester-based TPU (heel tips)	FTIR	Dibutyl adipate and adipic acid	FTIR	[58]
	Mining hammer handle (1970s), Deutsches Bergbau Museum Bochum	Polyester-based TPU (handle)	ATR-FTIR	Adipic acid	ATR-FTIR	[34]
	George Best football boots, Adidas Milano (1976), private collector	Polyester-based TPU (sole)	FTIR	Calcium sulphate dihydrate	FTIR	[59]
	Pelé football boots, likely Yasuda (1969), private collector	Aromatic (MDI) polyester-based TPU (sole)		Suberic acid		
	Gaizka Mendieta's *Milenia* boots, Kelme (ca.1999)	Polyester-based TPU (sole) (identification not confirmed)	-	Adipic acid or an adipate (suggested, not confirmed)	-	[60]

*μ = micro; ER-FTIR = External reflection-Fourier transform infrared.

Active and preventive conservation for TPU-coated fabrics with blooming: strategies and key findings

The conservation of TPU-coated fabrics presents significant challenges due to their multilayered construction and chemical instability. Although increasingly present in museum collections, these materials remain under-studied with regard to active conservation and preventive strategies, leaving conservators with limited reference tools [6, 12]. Furthermore, while blooming is one of the most recurrent forms of deterioration in TPU-coated fabrics, there are currently no preventive conservation guidelines specifically tailored to prevent this phenomenon or to slow its progression once present. Existing recommendations are limited in number and address TPU-coated fabrics more broadly, focusing on the chemical instability of the coating. This section therefore outlines general preventive conservation guidelines for TPU-coated fabrics, followed by the limited active approaches described for objects exhibiting blooming.

Recommendations compiled from recent publications, including Reddy-Best and Ordoñez [7] and the *Glossy Surfaces* project [61], emphasize isolating TPU-coated fabrics to prevent contamination of nearby materials and reduce the risk of cross-reactions caused by volatile degradation products. Storage should minimize dust accumulation, mechanical stress and limit folds, while ensuring stable environmental conditions (14-18 °C; 40-50 % RH with minimal fluctuations) and good air circulation to dissipate volatile compounds [7, 61]. Light levels during display should remain below 50 lux, with dark storage preferred. Handling must be minimal and performed with nitrile gloves to prevent surface damage or material loss, especially when blooming is present. Regular monitoring every three to six months is strongly advised to detect early signs of deterioration [61]. It should be noted, however, that these recommendations [7, 61] are primarily based on practice-based knowledge rather than systematic, peer-reviewed studies specifically focused on TPU materials. As such, they should be interpreted as preliminary guidelines, highlighting the need for further material-specific and systematically validated research addressing these topics.

Support and storage materials also play a critical role in preservation outcomes [6, 23, 61]. Hanging should only be considered when the object's condition allows, as tension may exacerbate damage; otherwise, horizontal storage is recommended [6]. Furthermore, the contact between items and storage materials should be minimized. Carita's master's thesis [35] suggests capsule-style covers in silicone-coated polyester film to prevent such contact. Additionally, providing internal support to avoid deformation is advised [61]. Recent preliminary assessments conducted within the Glossy Surfaces, based on the visual evaluation of various collections from museums and storage archives, suggest that, among the storage materials tested, polyethylene foil, Tyvek, tissue paper, glass containers (when in direct contact with the coating), polyester film (such as Melinex and Mylar), or anoxic enclosures specifically with ATCO or Ageless absorbers were the least suitable. Pre-washed cotton and silicone-coated polyester film may be used, but with caution. So far, based on [61], the most stable storage conditions seem to be silicone-coated paper and anoxic enclosures with RP System Type-K absorbers or argon gas.

Active conservation interventions for TPU-coated fabrics remain limited and often present significant risks. Reddy-Best and Ordoñez [7] recommend avoiding dry cleaning, as it can cause peeling, blistering, tackiness, and material loss. Similarly, wet cleaning should only be performed when strictly necessary, as this can result in crumbling, discoloration, and disintegration. Minimizing movement and flexing to prevent delamination is also recommended.

Specific research on cleaning strategies for TPU-coated items exhibiting blooming is limited, and the few known attempts by museum professionals to remove blooming have generally yielded only temporary results. Recently, under the *Glossy Surfaces* [16-17, 35] and *InBloom* [22-23] projects, this topic has been further researched, namely the impact of several cleaning methods and storage conditions on blooming reoccurrence.

Initial cleaning attempts were undertaken by França de Sá et al. [17], who studied blooming removal from two aromatic polyester-based TPU-coated items. For this experiment, a designer pouch and a non-museum historical jacket (bought at a flea-market) were used. Dry and wet cleaning strategies were comparatively evaluated using digital microscopy, colorimetry, and infrared spectroscopy [17]. Initial tests of dry cleaning tools revealed low efficiency and unacceptable material loss, leading to their exclusion. Subsequent wet cleaning trials were designed based on the solubility of adipic acid, using water, ethanol, and water/ethanol mixtures applied through confined and non-confined systems. Among non-confined methods, distilled water proved the safest and most effective, whereas ethanol caused coating loss.

Confined systems showed better performance, with agar-agar gel (4 % in water) demonstrating the most effective and least damaging results. Other hydrogels were less effective, and ethanol addition did not improve outcomes. Although promising, these results remain limited by the use of flat TPU-coated fabric samples, the lack of long-term assessment of water exposure, and the exclusive focus on adipic acid-based blooming [17].

The long-term impact of the most promising cleaning options, the agar-agar gel and sponge with water, was further assessed by Tomás Ferreira et al. [22-23], along with the impact of several storage conditions and wrapping materials, including open-air, anoxic enclosures, raw cotton fabric and silicone-coated polyester film. Blooming reoccurrence on cleaned samples was assessed after six months and again after two years of natural aging. After six months [22], the increase in blooming was almost insignificant, which did not allow for definitive conclusions. After two years [23], however, blooming increase was markedly more pronounced in non-cleaned samples than in cleaned ones. Among the latter, agar-agar gel showed the best results, enabling a more homogenous removal of adipic acid, in agreement with earlier observations by França de Sá et al. [17]. Regarding the storage options, although further studies are required to clarify the role of wrapping materials in blooming development, preliminary results suggest that wrapping in cotton fabric may promote further degradation [23].

Overall, recent research has provided essential insights into safer and more effective strategies for the removal of blooming from TPU-coated fabrics. Nevertheless, the limited number of case studies highlights the need for broader investigations that incorporate a wider range of TPU-coated objects and chemical natures of blooming, to better assess active and preventive conservation strategies.

Conclusion

TPU-coated items have proven to be highly vulnerable materials in museum collections, and their inherent instability poses persistent conservation challenges. Literature demonstrates that blooming is a widespread damage in design and fashion objects containing TPU-coated fabrics. Its visible manifestations, including loss of gloss, color alteration, and surface whitening, frequently compromise the objects' display value and the designer's intended aesthetic.

The investigation into blooming definitions highlighted two distinct but complementary explanatory models. In polymer science and industry, the phenomenon is generally described as a migration involving phase separation and exudation of pre-existing low-molecular-weight components, such as additives. From the industrial literature, it was determined that the occurrence of blooming is strongly influenced by the TPU's initial formulation. Conservation science, dealing with aged and degraded TPU objects, links blooming to the appearance of white surface deposits. In addition, most conservation studies further relate these deposits to the TPU chemical aging, specifically the hydrolytic cleavage of polyester polyol soft segments. This reaction results in acidic by-products, often adipic acid, that appear at the TPU surface. However, some studies lack a detailed characterization of the TPU formulation, often only identifying the diisocyanate and polyol families. As a result, it is difficult to establish a correlation between specific TPU formulations and the occurrence of blooming. Thus, these views of blooming do not seem to arise from different field perspectives but from distinct temporal and material contexts in which the phenomenon is observed. Consequently, the same term is applied to describe the visual appearance of the damage or the underlying mechanism. Notwithstanding, both processes – additive migration and hydrolytic degradation – may occur simultaneously or sequentially, and both can result in whitish deposits at the TPU surface. However, no single explanation fully captures the complexity of this phenomenon. This raises the question of whether precise terminology should be adopted.

Across the reviewed case-studies on TPU materials exhibiting blooming, the phenomenon is mainly associated with TPUs formulated with polyester-based polyols and aromatic diisocyanates. Adipic acid is predominantly identified as the main white efflorescence on both coated fabrics and elastomeric objects, occasionally accompanied by related adipate salts, esters, or other dicarboxylic acids. ATR-FTIR remains the primary technique for identifying both TPUs and blooming compounds, frequently supported by Py-GC/MS, XRD, and SEM for compositional and morphological analysis. Despite its strong visual disruption, blooming is rarely documented through images, limiting systematic comparison and restricting the assessment of potential developmental stages (from amorphous to crystalline). To facilitate its identification, it is crucial to have studies categorizing blooming's morphology (powdery vs. waxy), form (granular, spherical, spiked), and scale. Although existing studies show consistency in blooming chemical composition, they are limited in number, lack standardized methodologies, and rarely correlate environmental conditions (during storage, exhibition, and loans) or the items' use history with blooming development, highlighting the need for broader and more systematic investigations.

Regarding conservation strategies for TPU-coated fabrics, research has established critical initial guidelines. Preventive measures reported in the literature mention stable environmental conditions (14-18 °C; 40-50 % RH) and good air circulation, with regular monitoring. Although blooming is a frequently observed damage, specific preventive measures to tackle it are lacking, and current approaches largely rely on active measures to remove surface deposits and slow down its reoccurrence. Research findings revealed that dry-cleaning methods are generally ineffective or potentially damaging due to the intrinsic fragility of TPU coatings, with limited studies assessing these risks. Wet confined cleaning using agar-agar gels has demonstrated promising results with the safe removal of adipic acid deposits. Long-term studies revealed continuous blooming growth on non-cleaned samples, and minimal reappearance in agar-agar gel cleaned ones after two years of natural aging. Storage conditions also proved to be critical, with raw cotton appearing to promote blooming reoccurrence and abrasion.

Despite these developments, major questions remain regarding the applicability of such cleaning systems to materials presenting different surface textures and dimensions, as well as their effectiveness in removing blooming compounds other than adipic acid. Further research on storage materials is needed to determine their influence on the reoccurrence of all types of blooming compounds after cleaning treatments, and to identify the most effective in the long term. Moreover, the literature does not currently address the perspectives of designers or object owners on how blooming possibly impacts the interpretation, display, and public experience of TPU-coated objects, nor on ethical considerations regarding its removal.

The *InBloom* project will continue addressing these gaps through systematic research, contributing to evidence-based guidelines for the preservation of TPU-coated fabrics exhibiting blooming. Ultimately, this work aims to translate scientific findings into practical guidelines and decision-making tools that will support conservators in preserving these highly vulnerable materials across museum collections.

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REFERENCES

1. Rasmussen, S. C., 'Revisiting the early history of synthetic polymers: critiques and new insights', *Ambix* **65**(4) (2018) 356-372, https://doi.org/10.1080/00026980.2018.1512775.
2. Shashoua, Y., Conservation of plastics: materials science, degradation and preservation, Elsevier/Butterworth-Heinemann, Amsterdam (2008).
3. Chaudhary, M. L.; Gupta, R. K., 'Polyurethanes: an introduction', in *ACS symposium series*, eds. M. L. Chaudhary & R. K. Gupta, American Chemical Society, Washington, DC (2025) 1-14, https://doi.org/10.1021/bk-2025-1507.ch001.
4. de Souza, F. M.; Kahol, P. K.; Gupta, R. K., 'Introduction to polyurethane chemistry', in *Polyurethane chemistry: renewable polyols and isocyanates*, eds. R. K. Gupta & P. K. Kahol, American Chemical Society Publications, Washington, DC (2021) 1-24, https://doi.org/10.1021/bk-2021-1380.ch001.
5. Ghazal, H.; Saad, F.; Hegazy, B. M.; Sedik, A.; Hassabo, A. G., 'Polyurethane and its application in textile industry', *Letters in Applied NanoBioScience* **13**(1) (2024) 1-28, https://doi.org/10.33263/LIANBS131.008.
6. França de Sá, S.; Verkens, K.; Rizzo, A.; Petersen, G.; Scaturro, S.; Correia, I.; Carita, M., 'Synthetic coatings in fashion collections: identification and preservation issues', in *Handbook on museum textiles*, Scientific and Technological Research, Wiley (2023) 319-344.
7. Reddy-Best, K. L.; Ordoñez, M. T., Conservation concerns in fashion collections: caring for problematic twentieth-century textiles, apparel, and accessories, Costume Society of America, Ohio (2022).
8. Rodríguez Salinas, C.; Ferrazza, L., 'Real or faux leather? Luxury or ready-to-wear mass production? Characterization of three TPU shoe coatings (ca. 1970) from the Kunstmuseum Den Haag fashion collection', *Conservar Património* **47** (2024) 60-77, https://doi.org/10.14568/cp34780.
9. *Curating semi-synthetic and synthetic fibres and fabrics*, Dress and Textiles Specialists (DATS) and Plastics Subject Specialist Network (PSSN), London (2022), Microsoft Word - Curating Semi and Synthetic Fibres v1.docx, (accessed 2025-10-23).
10. Ionescu, M. (ed.), *Chemistry and technology of polyols for polyurethanes*, Rapra Technology, Shawbury (2005).
11. Meier-Westhues, H.-U.; Danielmeier, K.; Kruppa, P.; Squiller, E., *Polyurethanes: coatings, adhesives and sealants*, 2nd ed., Vincentz Network, Hannover (2019), https://doi.org/10.1515/9783748600473.
12. Tomás Ferreira, J.; De Vrieze, S.; Van Der Velde, E.; Verkens, K.; França de Sá, S., 'Beyond the surface: a closer look at the stratigraphy of synthetic-coated fabrics in fashion collections and commercial samples through optical microscopy', *Conservar Património* **47** (2024) 43-59, https://doi.org/10.14568/cp34830.
13. Fung, W., *Coated and laminated textiles*, CRC Press, Woodhead, Oxford (2008).
14. McSweeney, R. T.; Athey, R. J., 'Urethane coatings for textile substrates', *Journal of Coated Fabrics* **3** (1973) 16-30, https://doi.org/10.1177/152808377300300103.
15. 'Blooming (damage types)', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/page/Blooming (accessed 2025-10-23).
16. França de Sá, S., 'Mapping polyurethane coated fabrics and damages in fashion collections worldwide by optical microscopy and infrared spectroscopy', in *Semi-synthetic and synthetic textile materials in fashion, design and art,* ICOM-CC Modern Materials & Contemporary Art and Textiles Working Groups, Online (2023) in press.
17. França de Sá, S.; Tomás Ferreira, J.; Carita, M.; Correia, I.; Van Der Velde, E.; Verkens, K., 'A preliminary approach for blooming removal in polyurethane-coated fabrics', *Conservar Património* **47** (2024) 28-42, https://doi.org/10.14568/cp34728.
18. Bechthold, T., Polyurethan im möbeldesign der 60er jahre - technologie - alterung - konservierung. Unter besonderer Berücksichtigung polyurethanbeschichteter textiler Trägersubstrate, Master Dissertation, Restaurierung, Kunsttechnologie und Konservierungswissenschaft, Technische Universität München, München (2002).
19. 'Degradation of polyurethanes', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/page/degradation_of_polyurethanes (accessed 2025-10-23).
20. França de Sá, S., What does the future hold for polyurethane fashion and design? Conservation studies regarding the 1960s and 1970s objects from the MUDE collection, PhD dissertation, Department of Conservation and Restoration, NOVA School of Science and Technology, Caparica (2017).
21. Lavédrine, B.; Fournier, A.; Martin, G. (eds.), *POPART: Preservation of Plastic Artefacts in Museum Collections,* Comité Des Travaux Historiques et Scientifiques, Paris (2012).
22. Tomás Ferreira, J.; Damas, C.; Carita, M.; Correia, I.; Van Der Velde, E.; Verkens, K.; França de Sá, S., 'Oh no, not blooming again! Assessing the influence of storage conditions in the reappearance of blooming on TPU coated fabrics', poster in *Future Talks 023: Materials Matter. Cold and Current Cases in the Conservation of the Modern*, Die Neue Sammlung, Munich (2023).
23. Tomás Ferreira, J.; Laganà, A.; Mazurek, J.; Rizzo, A.; França de Sá, S., 'To clean or not to clean? Reversing a trend of conservation failures when dealing with blooming in thermoplastic polyurethanes', oral communication in *Future Talks 025: From failure to success. Innovative case studies in the conservation of the modern*, Die Neue Sammlung, Munich (2025).
24. *Inbloom*, https://sites.fct.unl.pt/inbloom/home (accessed 2025-12-11).
25. Seah, D. G. J.; Dasari, A., 'Establishing the bleeding and diffusion of chromophores from lining/upper fabrics in shoes to MidSole in sneakers – a case study', *The Journal of The Textile Institute* **116**(7) (2025) 1243-1251, https://doi.org/10.1080/00405000.2024.2372996.
26. Work, W.; Horie, K.; Hess, M.; Stepto, R., 'Definition of terms related to polymer blends, composites, and multiphase polymeric materials', *Pure and Applied Chemistry* **76**(11) (2004) 1985-2007, https://doi.org/10.1351/pac200476111985.
27. Wypych, G. (ed.), *Handbook of plasticizers*, ChemTec Pub, Toronto (2004).
28. Farkas, J., 'Thermoplastic polyurethane with reduced tendency to bloom from a bio-based glycol', Ohio, patent, US 2014/0107311 A1 (2014).

29. Farkas, J.; Jacobs, C. P., 'Thermoplastic polyurethane with reduced tendency to bloom', Ohio, patent, US 8,790,763 B2 (2014).
30. Farkas, J.; Day, R. W.; Gross, R. A.; Ganesh, M., 'Polyols with reduced cyclic oligomer content and thermoplastic polyurethane compositions thereof', Ohio, patent, WO 2017/040505 A1 (2017).
31. 'DAMIANI industrial paints: explanatory notes 2k top coats' (2019), https://www.betonboja.com/files/NE_DAM_TOP_COAT_2K_EN.pdf (accessed 2025-10-24).
32. França de Sá, S.; Ferreira, J. L.; Ramos, A. M.; Coutinho, B.; Macedo, R., 'How to keep what was intended to be temporarily functional? Reflections on decision-making for the conservation of polyurethane ready-to-wear fashion', in *Authenticity and replication: the 'real thing' in art and conservation*, eds. R. Gordon, E. Hermens & F. Lennard, Archetype, London (2014) 193-203.
33. Keneghan, B., 'A survey of synthetic plastic and rubber objects in the collections of the Victoria and Albert Museum', *Museum Management and Curatorship* **19**(3) (2001) 321-331, https://doi.org/10.1016/S0260-4779(01)00054-1.
34. Krieg, T.; Mazzon, C.; Gómez-Sánchez, E., 'Material analysis and a visual guide of degradation phenomena in historical synthetic polymers as tools to follow ageing processes in industrial heritage collections', *Polymers* **14**(1) (2021) 121, https://doi.org/10.3390/polym14010121.
35. Carita, M., A coleção de moda de Maria Gambina no MUDE – Museu do Design e da Moda: levantamento, caracterização material e desenvolvimento de estratégias de acondicionamento, Master Dissertation, Department of Conservation and Restoration, NOVA School of Science and Technology, Caparica (2022), https://run.unl.pt/bitstream/10362/155793/1/Carita_2022.pdf (accessed 2025-11-13).
36. Rizzo, A.; Scaturro, S., 'Already out of fashion: the fashionable rise and chemical fall of thermoplastic polyurethane', in *ICOM-CC 19th Triennial Conference Preprints*, ed. J. Bridgland, ICOM-CC, Beijing (2021) 1-11.
37. Lattuati-Derieux, A.; Thao-Heu, S.; Lavédrine, B., 'Assessment of the degradation of polyurethane foams after artificial and natural ageing by using pyrolysis-gas chromatography/mass spectrometry and headspace-solid phase microextraction-gas chromatography/mass spectrometry', *Journal of Chromatography A* **1218**(28) (2011) 4498-4508, https://doi.org/10.1016/j.chroma.2011.05.013.
38. Pellizzi, E.; Lattuati-Derieux, A.; Lavédrine, B.; Cheradame, H., 'Degradation of polyurethane ester foam artifacts: chemical properties, mechanical properties and comparison between accelerated and natural degradation', *Polymer Degradation and Stability* **107** (2014) 255-261, https://doi.org/10.1016/j.polymdegradstab.2013.12.018.
39. van Oosten, T.; Shashoua, Y.; Waentig, F., Plastics in art: history, technology, preservation, Siegl, Munich (2002).
40. van Oosten, T., *PUR Facts. Conservation of polyurethane foam in art and design*, Amsterdam University Press, Amsterdam (2011).
41. Sen, A. K., *Coated textiles: principles and applications*, 2nd ed., CRC Press, Boca Raton (2008).
42. Rose, A.; King, A., Plasticisers in historic plastics: spectroscopic and chromatographic approaches for cellulose acetate and polyvinyl chloride, PhD dissertation, Institute of Sustainable Heritage, University College London, London (2023).
43. Wei, X.-F.; Linde, E.; Hedenqvist, M. S., 'Plasticiser loss from plastic or rubber products through diffusion and evaporation', *npj Materials Degradation* **3**(1) (2019) 18, https://doi.org/10.1038/s41529-019-0080-7.
44. Szycher, M., *Szycher's handbook of polyurethanes*, 2nd ed., CRC Press, Boca Raton (2013).
45. Tomás Ferreira, J.; Rizzo, A.; Ferreira, G.; Carvalho, F.; Macário, D.; França de Sá, S., 'Vinyl- and polyurethane-coated fabrics in fashion collections: exploring material subtleties through a multi-analytical approach', *Heritage* **8** (2025) 511, https://doi.org/10.3390/heritage8120511.
46. Silva, C., Personal communication, Tintex, Vila Nova de Cerveira, Portugal (2025).
47. ISO 6452:2021. Rubber- or plastics-coated fabrics – Determination of fogging characteristics of trim materials in the interior of automobiles, International Organization for Standardization, Geneva (2021).
48. Farkas, J.; Jacobs, C. P., 'Thermoplastisches polyurethan mit verringerter ausblühneigung', Paris, patent, EP 2 408 831 B2 (2012).
49. Lavédrine, B.; Fournier, A.; Martin, G., 'Appendix 3: analysis of degradation products found during surveys of three French collections', in *POPART: Preservation of plastic artefacts in museum collections*, eds. B. Lavédrine, A. Fournier & G. Martin, Comité Des Travaux Historiques et Scientifiques, Paris (2012).
50. 'Case study - damaged blooming c1', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/item/75893 (accessed 2025-10-23).
51. 'Case study - damaged blooming c2', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/item/75899 (accessed 2025-10-23).
52. 'Case study - heavily damaged blooming c1', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/item/75889 (accessed 2025-10-23).
53. 'Case study - heavily damaged blooming c2', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/item/75891 (accessed 2025-10-23).
54. 'Case study - slightly damaged blooming c1', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/item/75892 (accessed 2025-10-23).
55. 'Case study - slightly damaged blooming c2', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/item/75886 (accessed 2025-10-23).
56. Bechthold, T., 'Wet look in 1960s furniture design: degradation of polyurethane-coated textile carrier substrates', in *The future of the 20th century: collecting, interpreting and conserving modern materials*, eds. C. Rogerson & P. Garside, Archetype Publications, London (2006) 128-133.
57. Bechthold, T., 'Tube, dixon and co. – And how are your elderly patients doing?', oral communication in *Future Talks 023: Material Matters. Cold and current cases in the conversation of the modern*, Die Neue Sammlung, Munich (2023).
58. Morris, R.; Keneghan, B., 'Cold war fashion: two case studies from an exhibition at the Victoria & Albert Museum', in *Future Talks 009: The conservation of modern materials in applied arts and design proceedings*, Die Neue Sammlung, Munich (2009) 93-100.
59. Spring, K.; Flexer, G., 'Approaching the preservation of polyurethane ester soles on football boots', in *University of Cambridge, Cambridge* (2023) 63-76, https://doi.org/10.17863/CAM.104118.
60. Llamas-Pacheco, R., 'Facing new challenges in the conservation of the boots of former Valencia Club de Fútbol player Gaizka Mendieta', Ge-conservacion **25**(1) (2024) 30-43, https://doi.org/10.37558/gec.v25i1.1186.

61. 'Conservation guidelines', in *Damage Atlas Glossy Surfaces*, https://studycenter.momu.be/DAT/page/conservation_guidelines (accessed 2025-10-23).

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