Sustainability versus Safety in 3D-Printed Tactile Aids for Blind Children: A Cross-Domain Review of Recycled Plastic Degradation, Chemical Risks, and Design Constraints, with an Illustrative Case

Yuhao Sun *

The International Department of South China Normal University Affiliated High School, Guangzhou, China

* Corresponding Author Email: sunyh.alex2024@gdhfi.com

Abstract. Desktop fused-deposition-modeling (FDM) 3D printing has made it possible to produce low-cost, customizable tactile educational aids for children with visual impairment, and the environmental cost of single-use virgin filament has encouraged the adoption of recycled and closed-loop ("distributed") filament. Three bodies of research bear on whether this substitution is safe for blind children: the engineering literature on how recycled polymers degrade, the environmental-health literature on the chemical emissions and migration of 3D-printed plastics, and the assistive-technology literature on how tactile aids are designed and used. These literatures rarely cite one another. This narrative review brings them together and reports three findings. First, recycled poly(lactic acid) (PLA), glycol-modified poly(ethylene terephthalate) (PETG), and acrylonitrile-butadiene-styrene (ABS) all lose measurable mechanical performance within only two to five reprocessing cycles, by polymer-specific mechanisms. Second, the chemical-safety profile differs sharply between polymers, with PLA the most favorable and ABS the least, and recycling can introduce non-intentionally added substances not present in virgin material. Third, tactile aids for blind children involve unusually high and prolonged skin and oral contact, placing them in the most demanding tier of toy-safety regulation. An illustrative case — a tactile sliding-block (Klotski) puzzle — shows that the same millimeter-scale raised features that carry the tactile information are simultaneously the most fragile and the highest-contact surfaces. Recycled filament should be treated as conditionally, not automatically, appropriate for this application, and material- and design-level constraints are set out together with priorities for future testing.

Keywords: Recycled plastics; distributed recycling; fused deposition modeling; poly (lactic acid); tactile educational aids; visual impairment; toy safety; chemical migration; circular economy; assistive technology.

1. Introduction

Recycled filament is increasingly used to 3D-print tactile educational aids for blind children, because it reuses plastic that would otherwise become waste. A material that looks greener, however, is not automatically safe for this use. Blind children explore learning objects with much more skin and mouth contact than other children, so a recycled aid that loses fine detail, wears down, or releases additional chemicals can pose risks that a virgin aid would not. The knowledge needed to weigh these risks sits in three separate research communities — polymer engineering, environmental health, and assistive-technology design — that rarely cite one another. This review reads the three literatures together for this demanding case.

1.1. Touch as the primary information channel

For children with visual impairment, touch is not a supplementary sense but the primary channel through which physical objects, symbols, and educational concepts are understood. The ability to interpret tactile representations develops gradually through childhood: in a study of textured tactile pictures, the proportion of elements correctly identified rose from about 33% among children aged five to seven years to 69% among adolescents aged thirteen to seventeen, and to 86.5% in adults, with exploration times lengthening as accuracy improved [1]. Because tactile interpretation is effortful and time-consuming, children handle tactile learning objects repeatedly and for extended periods.

Oral exploration — using the lips and tongue to perceive an object — is part of this tactile repertoire. The lips and tongue have spatial acuity equal to or greater than the fingertip, and a study of twenty blind or visually impaired adults found that, despite social discouragement, many continued to use the mouth to perceive texture, shape, and temperature, sometimes confirming with the mouth what the hand had first detected [2]. Mouthing is therefore not confined to infancy in this population; oral-tactile exploration is a documented compensatory strategy that can persist into adulthood. The practical consequence for material selection is that an educational object intended for blind children should be assumed to receive elevated and sustained contact through both the skin and the mouth.

1.2. 3D printing, sustainability, and recycled filament

Desktop fused-deposition-modeling (FDM) 3D printing has enabled teachers, families, and workshops to fabricate tactile maps, picture books, Braille labels, and manipulatives locally and at low cost. This flexibility comes with an environmental cost: virgin thermoplastic filament is energy-intensive to produce, and failed prints, supports, and prototypes generate substantial plastic waste. The field of distributed recycling for additive manufacturing (DRAM) — shredding plastic waste and re-extruding it into filament — has grown rapidly, alongside a commercial market in recycled filament [3]. A comparative life-cycle assessment found the environmental impacts of distributed recycling to be below 5% of the virgin supply chain in three of four categories examined [4]. Recycled-filament tactile aids are therefore both appealing and increasingly feasible.

1.3. Three literatures that do not meet

Whether recycled filament is safe for a blind child's tactile aid depends on knowledge that sits in three separate research communities (Fig. 1). The polymer-engineering community documents how recycled poly(lactic acid) (PLA), glycol-modified poly(ethylene terephthalate) (PETG), and acrylonitrile-butadiene-styrene (ABS) degrade with reprocessing. The environmental-health community documents the particles, vapors, and migrating chemicals associated with 3D-printed plastics. The assistive-technology community documents how tactile aids are designed and used. Each community treats material choice within its own frame — as a mechanical variable, a chemical variable, or a usability variable — and the three rarely cite one another. This review brings them into dialogue around a single, demanding application.

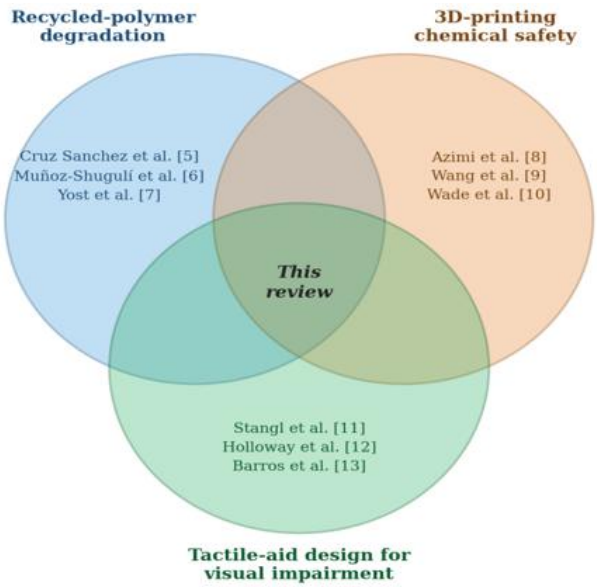

Fig 1. The three review domains and their intersection.
Representative sources shown in the figure: recycled-polymer degradation [5], [6], [7]; 3D-printing chemical safety [8], [9], [10]; tactile-aid design [11], [12], [13].

1.4. Review questions

The three research questions are as follows. (RQ1) How have the mechanical and thermal properties of recycled PLA, PETG, and ABS changed after multiple reprocessing cycles in FDM? (RQ2) What chemical exposure data have been collected for 3D-printed parts used in child-facing applications, and how do recycled feedstocks alter these exposures? (RQ3) What are the design parameters and use cases of tactile aids for blind children, and how are they related to material selection?

2. Mechanical and Thermal Degradation of Recycled Polymers in FDM

2.1. Recycled PLA

PLA is a typical desktop filament and has been studied more in closed-loop recycling. In the typical study of the closed FDM loop, after five recycling cycles, both the tensile strength and strain at break decreased significantly , accompanied by visible darkening [5]. An earlier closed-loop study reported that after only two printing cycles, the properties of PLA had significantly degraded and could not be reused [14]. The underlying chemistry is as follows: Over six melt-extrusion cycles of commercial PLA water-bottle preforms - which are not FDM but mechanistically relevant - the crystallinity increased from 6.9% to 39.5%, the melt-flow index more than doubled (from 65 to 137 g/10min), and the molecular weight dropped by as much as 40% [6], signatures of chain scission.

Single-cycle degradation is relatively small; after one cycle, recycled PLA has lost 10.9% of its tensile strength and decreased by 2.4% in hardness, but the elastic modulus remained almost the same, there was more variation among the samples, and occasional nozzle clogging occurred [15]. The first round is lenient, but the accumulated losses of several rounds are not. The values of the endpoints are shown in Figure 2 and Table 1.

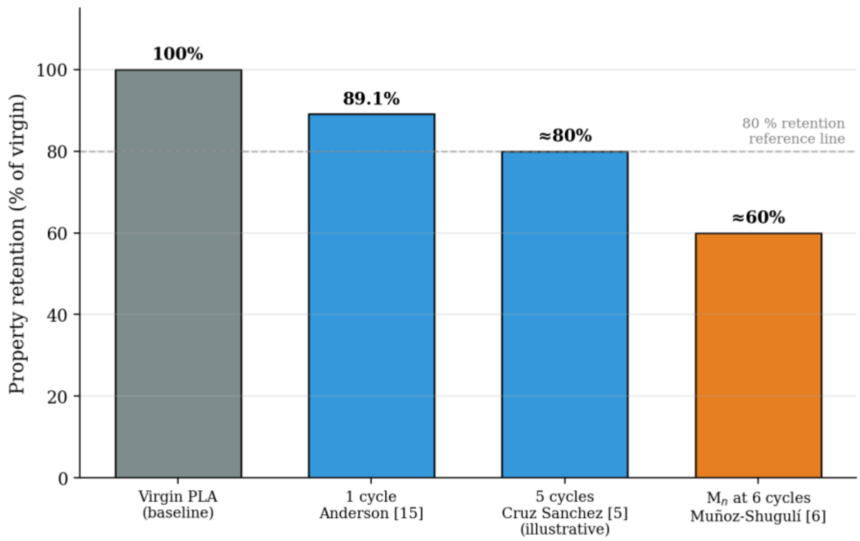

Fig 2. Reported property retention of recycled PLA after reprocessing, compiled from [5], [6], [15]. Values refer to different properties and contexts and are not a single continuous dataset. Dashed line: 80% retention reference.

2.2. Recycled PETG

PETG has good impact strength and durability; therefore, it is suitable for objects that are frequently dropped or handled roughly. The chemistry of its recycling determines recyclability. Based on the study of three commercial PETGs after six print-and-reprocess cycles, the elastic modulus and tensile strength were largely maintained for five prints, but ductility (the capacity to deform without fracture) decreased significantly after only one recycle for the grade with the lowest cyclohexanedimethanol (CHDM) content [7]. PETG is also hydrolytically unstable; that is to say, it reacts with water, so pre-drying of the filament is required, otherwise trapped moisture will cause bubbling and chain scission during printing [16]. Recycled PETG is thus feasible to use but more sensitive to careless handling than virgin PETG, and its properties are affected by a copolymer parameter that consumers are unable to observe from the spool.

2.3. Recycled ABS

ABS is a two-phase material; it has a hard styrene-acrylonitrile (SAN) matrix and dispersed polybutadiene rubber particles. The rubber phase is the weak link; repeated processing causes oxidation and the formation of carbonyl groups (a growing infrared peak near 1721 cm-1), loss of carbon-carbon double bonds that provide toughness to the rubber, and thus embrittlement and yellowing [17]. By the third recycling round of FDM ABS, the strain at break and tensile strength have decreased by about 25% and 10%, and the porosity has risen from approximately 11 to 17 vol% [18]. The literature is not in agreement; another group showed a temporary increase in the fifth cycle before a decline, possibly reflecting annealing rather than real strengthening [19].

2.4. Common mechanisms and a scale argument

The three degradation mechanisms are repeatedly occurring: hydrolytic chain scission (cleavage of the ester backbone by water in PLA and PETG), thermo-oxidative chain scission (repeated heating in air), and oxidation of the rubber phase (specific to ABS). All reduce molecular weight and shift properties toward brittleness.

A point that bulk-property data do not directly address concerns geometry. Mechanical tests use dog-bone specimens several millimeters thick, while tactile aids carry information in features — dots, ridges, raised symbols — often a fraction of a millimeter to one or two millimeters in size. Small features concentrate stress, present a higher surface-area-to-volume ratio for oxidation and hydrolysis, and have less material to spare before a crack propagates through. Bulk measurements therefore systematically understate the integrity loss of the features that make a tactile aid usable — an inference from mechanism rather than measurement (see Section 8).

Table 1. Recycled PLA / PETG / ABS — reported property changes across reprocessing cycles.

Polymer	Key reported change	Cycles	Source
PLA	Significant decrease in tensile strength and strain at break; filament darkening	5	Cruz Sanchez et al. [5]
PLA	Usable for only ~2 reprocessing cycles before sharp property loss	2	Zhao et al. [14]
PLA	Crystallinity 6.9% to 39.5%; MFI 65 to 137 g/10 min; molecular weight up to -40%	6	Muñoz-Shugulí et al. [6]
PLA	Tensile strength -10.9%; hardness -2.4%; modulus unchanged (higher variability)	1	Anderson [15]
PETG	Modulus and tensile strength retained; ductility falls after 1 recycle (low-CHDM grade)	5	Yost et al. [7]
ABS	Strain at break -25%; tensile strength -10%; porosity 11% to 17%	3	Cress et al. [18]
ABS	Apparent improvement to 5th cycle, then deterioration (contested)	5	Vidakis et al. [19]

3. Chemical Safety of 3D-Printed Plastics in Child-Facing Applications

3.1. Emissions during printing

FDM printing releases ultrafine particles (UFPs, smaller than 100 nm) and volatile organic compounds (VOCs) as the heated filament is extruded. In a widely cited chamber study, emission rates ranged across many orders of magnitude depending on material: ABS released styrene at roughly 10 to 110 micrograms per minute, whereas PLA released its characteristic compound, lactide, at only about 4 to 5 micrograms per minute [8]. The difference in particles is just as stark: ABS printing produced particle concentrations 33 to 38 times higher than PLA under comparable conditions [20].

These exposures matter most for the youngest users. Using a respiratory-deposition model to translate measured emissions into internal dose, a U.S. Environmental Protection Agency team found that ABS produced greater particle exposure than PLA, that most particle mass deposited in the deep (pulmonary) region of the lung, and — critically — that children received higher predicted pulmonary deposition than adults, identifying them as a potentially susceptible population because of both their exposure and the developmental state of their airways; the same study noted that desktop printers are increasingly used in schools and libraries [21]. For a tactile aid printed in or near a classroom, low-emission material and adequate ventilation are thus child-protection measures, not just housekeeping.

3.2. Migration into saliva and sweat

For an object that is handled and mouthed, the dominant exposure is not inhalation during printing but migration out of the finished part into saliva and sweat. PLA performs well here: lactic acid, lactide, and oligomer migration into food simulants was measured at 0.28 to 15 micrograms per square centimeter at 40 C over 180 days — well within tolerable limits at body temperature, rising steeply only at elevated temperatures [22]. ABS is more concerning: modeling the migration of residual styrene and acrylonitrile from 94 commercial ABS toys into saliva yielded estimated lifetime cancer risks on the order of 10-8 to 10-6 for each substance [9]. Applying the standard toy-safety saliva-simulant protocol to FDM filaments, pure PLA passed while metal-filled "composite" filaments did not: the metal particles were not chemically bound to the polymer and could migrate and become bioavailable [10]. Additives and fillers, not the base polymer alone, can determine whether a printed part is mouth-safe.

3.3. Recycled feedstock as a vector for unknown substances

Recycling can introduce chemicals that were not originally in the virgin material — non-intentionally added substances (NIAS) such as residual colourants, processing aids, contaminants from the previous life of the product, and catalyst residues. The first example is the closely related polymer PET, and as shown in [23], recycled streams have been repeatedly found to contain higher levels of antimony (a polymerization catalyst) and other migrants than virgin material. PETG is chemically related to PET, so some carry-over from recycled PETG is expected, but it has not been fully studied. A home or workshop recycling stream is less regulated than an industrial food-grade line; it has mixed colours, varying grades and unknown histories, and therefore the chemical identity of recycled filament is inherently less certain than that of a sealed virgin spool.

3.4. A surface-integrity pathway: microbial colonization

A consideration specific to mouthed objects is that FDM parts are not smooth. The layer-by-layer process leaves regular ridges (typical layer height on the order of 100 to 200 micrometers), and this roughness provides attachment sites for bacteria and biofilm formation on printed PLA surfaces [24]. For a toy that is frequently handled and mouthed and infrequently sterilized, surface texture is thus a hygiene variable as well as a tactile one.

3.5. The regulatory perimeter — and what falls outside it

Toy chemical safety is governed by mature standards. EN 71-3:2019+A2:2024 sets migration limits for nineteen elements (including antimony, lead, cadmium, hexavalent chromium) across three toy-material categories, and the broader toy-safety framework gives special attention to toys intended to be placed in the mouth [25]. In the United States, ASTM F963-23 is the mandatory standard, enforced under the Consumer Product Safety Improvement Act [26]. Selected limit values are compared in Table 2. Neither standard certifies a 3D-printed part as food-contact-safe, accounts for the porous layered surface, or differentiates a high-contact tactile aid from an ordinary toy. A printed part can satisfy elemental-migration limits and still sit outside the assumptions — smooth surfaces, controlled material, ordinary contact — on which the standards were built.

Table 2. Selected elemental migration limits, ASTM F963-23 vs EN 71-3 Cat. III (mg/kg of toy material). The two frameworks are not one-to-one; values are indicative only.

Element	ASTM F963-23 (soluble)	EN 71-3 Cat. III (scraped-off, indicative)
Antimony (Sb)	60	560
Arsenic (As)	25	47
Barium (Ba)	1000	18 750
Cadmium (Cd)	75	17
Chromium (Cr)	60	Cr(III) 460 / Cr(VI) 0.053
Lead (Pb)	90	23
Mercury (Hg)	60	94
Selenium (Se)	500	460

4. 3D-Printed Tactile Aids for Blind Children: Design and Use

4.1. Foundational projects and conventions

3D printing for blind and visually impaired learners has a decade of design precedent. Early projects produced tactile picture books co-designed with educators [11]. A three-year study in special-education settings documented how 3D printing was adopted to fabricate assistive objects and the practical obstacles teachers faced [27]. In a controlled comparison, three-dimensional printed models were preferred by touch-readers over conventional raised-line tactile graphics, supported clearer icons, and improved short-term recall of map content [12]. The consistent message is that physical, three-dimensional tactile features are effective — which makes the integrity of those features a usability requirement, not a cosmetic one. Table 3 summarizes representative studies and the material each report.

Table 3. Selected 3D-printed tactile-aid studies — application, material, evaluation method.

Study	Application	Material reported	Evaluation
Stangl, Kim and Yeh [11]	Tactile picture books	Virgin filament (design probe)	Co-design with educators
Buehler et al. [27]	Assistive objects in special education	Virgin filament (assumed)	3-year qualitative study
Holloway, Marriott and Butler [12]	Tactile maps	Virgin filament	Controlled study, 16 touch-readers
Barros, Correia and Teixeira [13]	Tactile content (general)	Virgin PLA	Print-adherence / dimensional study

4.2. Dimensional parameters of tactile legibility

Tactile legibility depends on feature geometry. A study of 3D-printed tactile content for visually impaired users found that line widths between 0.8 and 1.2 mm gave good print adherence, and that 0.4 mm was about the maximum feature height that could be printed reliably without compromising adhesion [13]. Features must therefore be large enough to be felt and distinguished, but the printing process constrains how fine and how tall they can be — placing tactile features squarely in the small-feature regime where the scale argument of Section 2.4 applies.

4.3. Use patterns and the gap

Three use patterns distinguish tactile aids for blind children from ordinary toys: prolonged manual handling (since tactile interpretation is slow and improves with exploration time [1]), repeated contact on the same informative surfaces, and elevated oral exploration [2]. The most informative features are therefore also the features touched most often, for the longest time, and most likely to reach the mouth. Across this literature, however, material is treated almost entirely as a usability variable under the near-universal assumption of virgin filament; the recycling literature is not engaged. This is the gap addressed here.

5. Illustrative Case: A Tactile Klotski for Blind Children

5.1. Case description

The case is a tactile sliding-block puzzle — a Klotski — designed for use by children with visual impairment. In a conventional Klotski, blocks of different sizes are slid within a frame to reach a goal configuration; the blocks are visually distinguished. For a blind player this visual distinction is unavailable. The design intent is therefore to give each block a distinct pattern of raised features at different positions, so that a player can identify each block, and track its orientation, entirely by touch (Fig. 3).

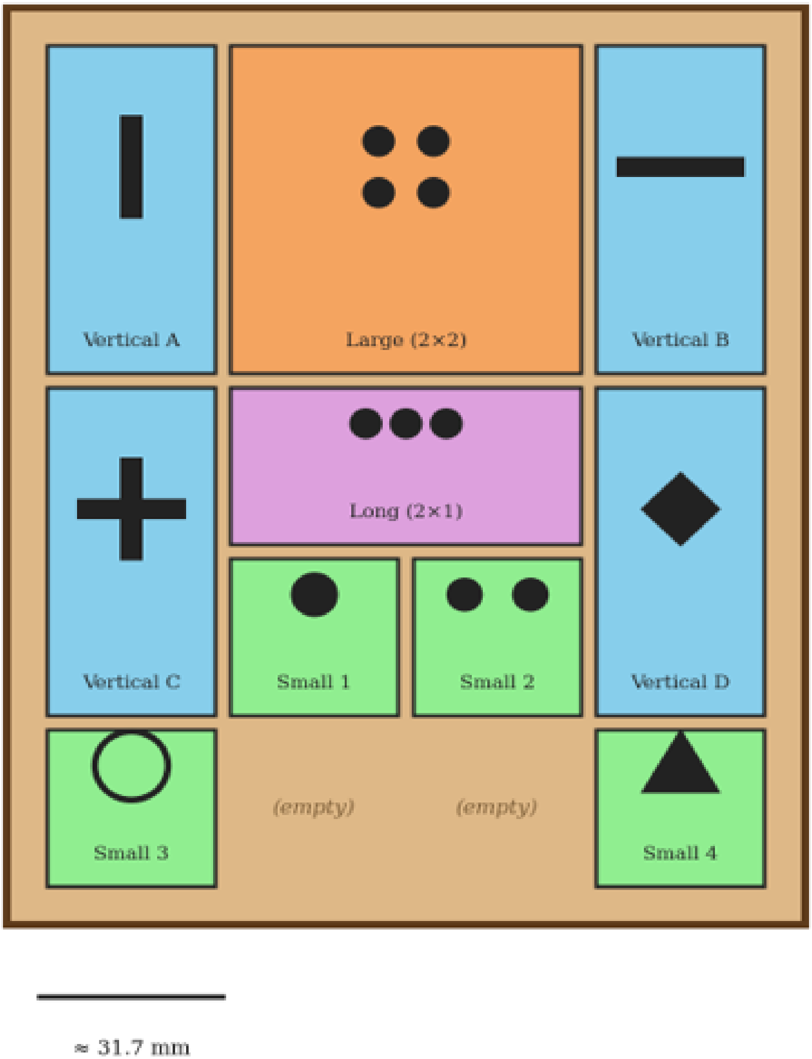

Fig. 3 Schematic of the tactile Klotski (top view).
Each block carries a distinct raised-feature pattern for touch identification.

5.2. Design choices

The current design distinguishes blocks by the position and arrangement of small raised features on their faces, rather than by size alone. An earlier iteration attempted to distinguish blocks using flat, cut-out (hollow) patterns, but these proved difficult to discriminate by touch and were replaced by the raised-feature approach — an informal demonstration that protruding features carry tactile information more effectively than recessed ones. The blocks were printed in PLA Basic filament on an open-frame desktop printer (Bambu Lab A1) using standard slicer settings. The prototype used virgin PLA; a recycled-feedstock version of the same design would face the constraints identified in the following subsections.

5.3. Re-reading the design through the review

By reading the design back through Sections 2 to 4, one can reorder it according to a single physical fact: the raised features are simultaneously the carriers of information (Section 4), the most fragile parts (Section 2), and the surfaces in highest and most oral contact (Sections 1.1 and 3.2).

5.4. Observation 1: the fragility of small features

The difficulty of the early flat-pattern iteration, and the choice of raised features, place the most important elements in exactly the small-feature regime where degradation is expected to bite hardest (Section 2.4). Even in virgin PLA, repeated sliding and handling will wear and round small protrusions; in recycled PLA, whose molecular weight and ductility are already reduced (Section 2.1), the margin before a feature chips or flattens is smaller still. The feature that makes the toy usable is the feature most likely to fail first.

5.5. Observation 2: contact dose and the strictest safety tier

Because the intended users handle the blocks at length and may bring them to the mouth (Sections 1.1, 4.3), the object belongs in the most stringent tier of toy-safety expectation — toys intended to be placed in the mouth (Section 3.5). The choice of PLA is fortunate: PLA's migration and emission profiles are the most favorable of the three polymers (Sections 3.1 to 3.2). The open-frame printer does not enclose emissions, but PLA's low emission rate mitigates this. A recycled version, however, would reintroduce the NIAS uncertainty of Section 3.3 that a virgin spool does not carry.

5.6. Design revisions implied by the review

The three revisions and their trade-offs among the three risk axes are shown in Figure 4. First, feature geometry: The size of the raised features should be within the reliable-printing range (around 0.4 mm height, Section 4.2), but with a large radius and base rather than a sharp, thin protrusion, to resist wear and reduce stress concentration. Second, feedstock provenance: If recycled PLA is used, it should be from a known single-source stream (e.g., a workshop's own failed PLA prints) rather than mixed post-consumer waste, and uncolored or single-colour stock should be preferred to limit NIAS and pigment migration. Third, a processing limit: Recycling should be limited to a small number of cycles, about two or three, and the feedstock supplemented with virgin PLA in accordance with the degradation data in Section 2.1.

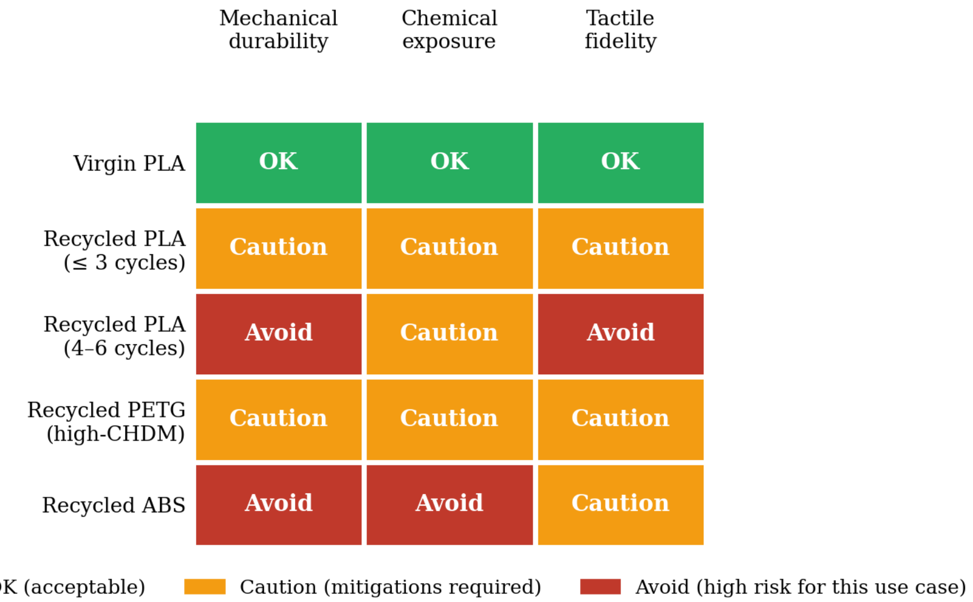

Fig 4. Material choices vs. three risk axes: mechanical durability, chemical exposure under blind-child use, and tactile fidelity. Cells: OK, Caution, Avoid.

6. Discussion: Cross-Domain Synthesis

Bringing the three literatures together leads to geometry: the mechanical results (Section 2), the chemical results (Section 3) and the design results (Section 4) all point to the same small raised features, which are at the same time the information carriers, the first failure sites, and the high-contact surfaces. Toy safety standards regulate elemental migration without distinguishing by use pattern; the recycling literature frames recycled filament as a sustainability gain without an application-specific safety lens; the tactile-aid literature treats material as a usability variable and assumes virgin feedstock. The blind-child tactile-aid case sits where none of the three frames is sufficient on its own. Recycled filament for this application is best described as conditionally suitable: it can be used if the material, cycle number, source of feedstock, and feature geometry are all controlled together.

This reframes sustainability-versus-safety as conditional rather than opposing. A good-performing, mouth-safe recycled-PLA aid that is also environmentally friendly is better than one that degrades and must be thrown away after only a few weeks, even though a virgin aid will last longer. Sustainability is contingent on durability and safety; it does not replace these. The same logic applies to the circular economy more broadly. Recycled plastic is only a genuine environmental gain if the finished aid stays strong and chemically safe through long skin and mouth contact. The degradation described in Section 2 bears directly on this: PLA loses strength and ductility over repeated cycles, while PETG and ABS can become brittle depending on how they are processed. If recycled material makes the small raised features chip, wear, or shed particles, the aid has to be reprinted and replaced every few weeks. The added waste and shorter life can then outweigh the benefit of keeping plastic out of the virgin supply chain. So sustainability here is conditional: it depends on the specific material, the cycle count, and the feature size, not on the recycled label alone. Fig. 4 sets out how the common materials compare across these risks.

7. Limitations

This is a narrative rather than a systematic review; therefore, source selection was guided by the three-domain framing rather than a pre-registered search protocol, and some relevant work may have been missed. The illustration is a single design that has not undergone independent user evaluation or instrumented testing. No primary experimental data are presented; all materials and properties, as well as emission and migration values, have been taken from the cited literature, and the scale argument in Section 2.4 is an inference based on the mechanism. Some safety claims for recycled PETG are derived from studies on recycled-PET, and there is an outstanding contradiction in the mechanical data of recycled-ABS (Section 2.3).

8. Future Research Directions

Three priorities follow. Empirically: characterize commercial recycled PLA on geometries representative of tactile features (not bulk dog-bone specimens), measuring both initial fidelity and durability under repeated abrasion, and run EN 71-3 saliva-migration testing on the same geometries. Methodologically: user studies with blind children and their teachers to characterize realistic contact-dose profiles, since current safety assumptions are not calibrated to this population. Regulatory: examine whether high-contact tactile aids for visually impaired users warrant a defined sub-category within existing toy-safety frameworks, analogous to the treatment of toys intended to be placed in the mouth.

9. Conclusion

Recycled plastics offer a route to more sustainable tactile educational aids for blind children, but their suitability cannot be read off the sustainability case alone. The mechanical, chemical, and design literatures converge on the small raised features that carry tactile meaning, are the first to degrade, and receive the most skin and oral contact. For this application, recycled filament is conditionally appropriate — favoring PLA, low cycle counts, known single-source feedstock, and robust feature geometry. Safe design at this intersection requires reading the three literatures together. That integration is the review's central contribution. Read as one problem, the three literatures point to a practical way to balance safety and sustainability for recycled 3D printing in special education. In this framework, a recycled material is judged not by its environmental appeal alone, but by three linked criteria: whether the tactile features stay mechanically durable, whether they stay chemically safe under heavy skin and mouth contact, and whether they remain easy to read by touch. For makers, schools, and accessibility organizations, this offers a starting point for choosing materials rather than a finished standard. Turning it into a settled standard would still require direct testing — of how the recycled materials wear, what they release chemically, and how blind children actually use the aids — that has not yet been done.

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