Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.37146

The Limits of Evidence-Based Material Selection for Children's 3D-Printed Tactile Learning Aids: A Structured Re-analysis of Polylactic Acid, Glycol-Modified Polyethylene Terephthalate and Acrylonitrile Butadiene Styrene

Yuhao Sun

The International Department of South China Normal University Affiliated High School, Guangzhou, China
sunyh.alex2024@gdhfi.com

Abstract. Low-cost material extrusion has made customised tactile learning aids available to children with visual impairment, but the literature comparing polylactic acid (PLA), glycol-modified polyethylene terephthalate (PETG) and acrylonitrile butadiene styrene (ABS) does not state which polymer such an aid should use, and the application literature does not report the filament it employs. Reported values were extracted from fifteen sources under a declared protocol, normalised, and combined in a weighted decision model with a sensitivity analysis over criterion weights and over three treatments of cells for which no evidence exists. Three results follow. Elastic modulus ranges for individual commercial PLA and PETG grades overlap between 1041 and 1377 MPa across two laboratories, so supplier identity outweighs polymer identity. ABS attains first rank in none of 10,626 sampled weight vectors. The durability weight at which PETG replaces PLA moves from 0.32 to 0.45 according only to how untested cells are treated. Recommendations at polymer level are therefore unsupported; selection must specify grade, process parameters and service conditions.

Keywords: fused filament fabrication, tactile learning aids, material selection, toy safety, multi-criteria decision analysis

1. Introduction

Tactile learning aids convey spatial and scientific concepts to children through touch, and low-cost material extrusion has made them inexpensive enough to customise for an individual learner. Controlled evaluation supports their use: in a study with sixteen touch readers, three-dimensional printed models were preferred over conventional tactile graphics, produced better short-term recall, and made the relative height of features easier to interpret [1]. The geometry that carries the information is small. Minimum horizontal spacing between tactile symbols has been evaluated at one, two and three millimetres with thirty visually impaired participants; height differentiation between symbols allowed that spacing to be reduced without loss of legibility [2].

DOI: 10.54254/2755-2721/2026.37146

Those raised features are simultaneously the parts of an aid that take fingertip loading, that are abraded by repeated tactile scanning, and that material extrusion reproduces least accurately. Neither study cited above states which filament was used, and the comparative polymer literature reports properties measured on standard tensile specimens rather than on objects a child handles. Fabrication emissions, chemical migration and mechanical characterisation are published in separate venues and rarely cite one another. No located study has tested a finished printed teaching aid against EN 71-3, ISO 8124-3 or ASTM F963-23, the instruments that would govern a commercially manufactured equivalent.

The question addressed here is narrower than which polymer performs best: under what conditions can the published evidence support a material choice at all, and what does it demonstrably fail to support. Reported values for polylactic acid (PLA), glycol-modified polyethylene terephthalate (PETG) and acrylonitrile butadiene styrene (ABS) were extracted under a declared protocol, normalised, and combined in a weighted decision model. The stability of the resulting ranking was then examined against the criterion weights and against three treatments of the cells for which no measurement exists. The contribution is the boundary of validity rather than the ranking itself. Five criteria are used, spanning fabrication exposure, migration from the finished article, mechanical durability, life-cycle burden and the retention of tactile detail.

2. Method

Fifteen sources were retained from a structured search of OpenAlex covering the application domain, fabrication emissions, product-stage migration, mechanical characterisation, ageing, recycling and multi-criteria selection methods. Sources were retained when they tested two or more of the three polymers under stated conditions, reported numeric values with units, or supplied child-specific exposure evidence. Every reference was resolved against Crossref before inclusion.

Extracted values populate five criteria: fabrication safety, product-stage safety, durability, sustainability and tactile fidelity. Each criterion is the mean of its normalised sub-criteria, whose extracted values are listed in Table 1. Values sharing a unit were normalised linearly between the best and worst observed value and oriented so that unity is preferable. Three sub-criteria are ordinal and their encodings are declared: relative particle response at equal mass dose [3]; a two-level migration rubric in which a quantified child-exposure pathway is the higher concern level and therefore scores worse than migration conditional on service temperature; and a bio-based feedstock indicator scored one for yes and zero for no.

Cells for which no evidence was located were not filled with a default value. They were propagated as missing and resolved by three declared treatments, optimistic, neutral and pessimistic, which assign the best observed, mean observed and worst observed value respectively. Ranking used the technique for order of preference by similarity to ideal solution, following its application to orthosis material selection [4]. Stability was assessed by sweeping the durability weight, by sweeping the combined safety weight, and by sampling the five-dimensional weight simplex at five per cent resolution. Standards are cited by designation rather than as reference entries, and no test was performed here, so no claim of conformity to any of them is made.

DOI: 10.54254/2755-2721/2026.37146

Table 1. Extracted values by sub-criterion and polymer, with source reference numbers; the marker volatile organic compound is named in each cell

Sub-criterion (source)	PLA	PETG	ABS
Particle emission rate, min^{-1} [5]	2.0×10^{10}	not located	1.9×10^{11}
Marker organic compound, μg min^{-1} [6]	5, lactide	not located	110, styrene
Particle response, equal mass [3]	higher	not located	lower
Product-stage migration [7, 8]	conditional	not located	quantified, children
Elastic modulus, MPa [9]	1346.4	905.6	1030.0
Maximum stress, MPa [9]	48.0	51.3	42.8
Toughness, kJ m^{-3} [9]	159.2	334.4	256.7
Water uptake at 30 days, % [9]	1.04	0.30	0.96
Recycling cycles shown [10]	not located	6	not located
Bio-based feedstock [11]	yes	no	no

3. Evidence base

3.1. Safety: fabrication emissions and product-stage migration

Fabrication emissions favour PLA by a wide margin. Reported ultrafine particle emission rates are approximately 2.0×10^{10} per minute for PLA and 1.9×10^{11} per minute for ABS from the same printer type [5]. Speciated measurement gives styrene at 10 to 110 μg per minute from ABS against lactide at 4 to 5 μg per minute from PLA [6].

The ordering inverts once particle toxicity rather than particle quantity is considered. At comparable mass doses, particles emitted from PLA elicited higher responses than particles emitted from ABS in both cellular assays and mouse exposure; ABS remains the greater concern in overall exposure only because it emits far more mass [3]. Children are the more exposed receptor, deposited particle surface area normalised to pulmonary surface area peaking in the nine-year-old age group [12].

The ordering inverts a second time at the product stage. Migration from PLA is conditional on temperature: reported migration from food-contact sheet reaches 15.0 μg cm^{-2} after 180 days at 40 °C but 2840 μg cm^{-2} after only 10 days at 60 °C, the lower bounds of those ranges being 0.28 and 0.73 μg cm^{-2} [7]. For ABS, validated models applied to 94 toys have quantified styrene and acrylonitrile exposure for children aged three months to three years [8]. For printed PETG no equivalent study was located.

3.2. Durability: parameter dominance and rank-order instability

Process parameters govern printed mechanical performance more strongly than polymer identity. Raising ABS infill from 20 to 50 per cent improves ultimate tensile strength by 26 per cent, yield stress by 24 per cent and elastic modulus by 45 per cent, and infill followed by layer thickness is the most influential parameter across all four polymers that study examined [13].

Published rankings are not consistent. One study concludes that PLA exceeds PETG on modulus and strength while the thermal deformation ordering is reversed [14]. A second, testing two commercial grades of each polymer under identical conditions, places the better PETG grade above the better PLA grade on yield strength [15]. A third, testing all three polymers on one machine with parameters held identical apart from a material-specific nozzle temperature (230, 250 and 260 °C), reports maximum stress of 51.3 MPa for PETG against 48.0 MPa for PLA and 42.8 MPa for ABS, toughness of 334.4, 159.2 and 256.7 kJ m^{-3} respectively, and 30-day water uptake of 0.30, 1.04 and 0.96 per cent [9].

Figure 1(a) places the individual grades from the last two studies on one axis. The two PLA grades of [15] span 1041 to 1481 MPa and the two PETG grades span 900 to 1377 MPa, while the single-machine values of [9] fall inside the corresponding ranges. PLA and PETG overlap between 1041 and 1377 MPa. Variation between suppliers and between laboratories therefore exceeds the difference between polymers that each study reports as its own result.

3.3. Sustainability: modelling choices and the cost of reprocessing

Life-cycle rankings for material extrusion follow modelling choices rather than polymer identity alone. Process electricity, build parameters and end-of-life handling are recognised determinants, and a comparison stated per kilogram of filament rather than per unit of educational service delivered will mis-rank the alternatives [11].

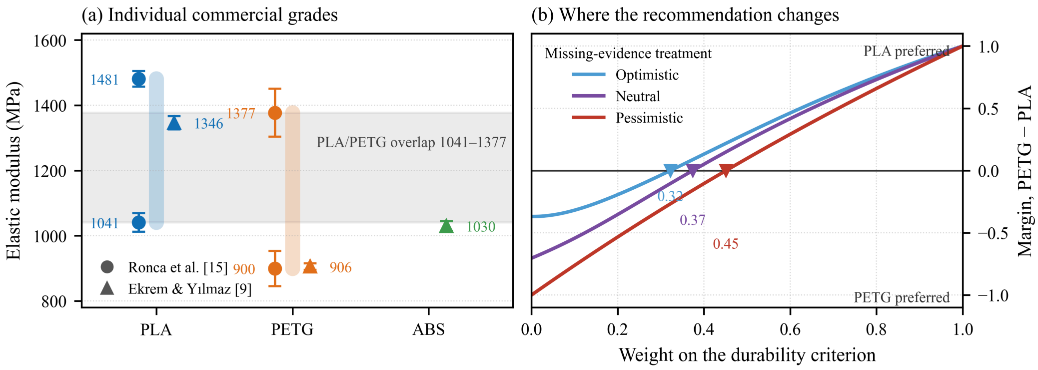

Figure 1. (a) Tensile elastic modulus of individual commercial grades measured in two independent laboratories, with the PLA and PETG ranges overlapping between 1041 and 1377 MPa; (b) closeness margin between PETG and PLA as the durability weight is swept, one curve per treatment of the cells for which no evidence exists

Recycling evidence is asymmetric. PETG has been reclaimed and reprinted through six consecutive cycles with only a minor reduction in tensile and flexural properties, but with a clear and progressive loss of impact strength, third and fourth cycle specimens behaving in a brittle manner [10]. No comparable multi-cycle measurement for PLA or ABS was located within the retained sources. The property that reprocessing degrades is therefore the property this application depends on, because a tactile aid fails by being dropped rather than by being pulled in tension. A functional unit expressed as one aid delivering a stated period of classroom service, rather than one kilogram of filament, would make that trade explicit.

DOI: 10.54254/2755-2721/2026.37146

4. Material-selection analysis

4.1. Weighted decision model and results

Table 2 reports criterion scores under equal weights for the neutral treatment, together with closeness coefficients and ranks under all three treatments of missing evidence. PLA ranks first in all three, with closeness coefficients of 0.689, 0.734 and 0.767 under the optimistic, neutral and pessimistic treatments. PETG ranks second under the optimistic and neutral treatments and third under the pessimistic treatment, where ABS displaces it.

That outcome reflects criterion counting rather than a safety verdict. PLA leads on four of the five criteria and loses only durability, by 0.478 points, the largest deficit it carries on any single criterion: toughness of 159.2 against 334.4 kJ m^{-3} for PETG, a factor of 2.1 [9].

Sampling the five-dimensional weight simplex at five per cent resolution yields 10,626 weight vectors. PLA ranks first in 64.7 per cent of them under the optimistic treatment, 85.0 per cent under the neutral treatment and 92.2 per cent under the pessimistic treatment, PETG taking the remainder. ABS attains first rank in none of the 10,626 vectors under any treatment, and is the only polymer that the analysis excludes on the evidence rather than on the weighting. That exclusion holds under every treatment of missing evidence and every sampled weight vector.

Table 2. Criterion scores under equal weights for the neutral treatment, with closeness coefficients and ranks under all three treatments of missing evidence

Criterion	Weight	PLA	PETG	ABS
Fabrication safety	0.20	0.667	0.500	0.333
Product safety	0.20	1.000	0.500	0.000
Durability	0.20	0.322	0.800	0.331
Sustainability	0.20	1.000	0.500	0.500
Tactile fidelity	0.20	1.000	0.000	0.282
Closeness (o / n / p)	-	0.69/0.73/0.77	0.50/0.38/0.23	0.17/0.17/0.27
Rank (o / n / p)	-	1/1/1	2/2/3	3/3/2

4.2. Weight sensitivity and rank stability

Figure 1(b) sweeps the weight assigned to durability while dividing the remainder equally among the other four criteria. The margin between PETG and PLA crosses zero at a durability weight of 0.32 under the optimistic treatment, 0.37 under the neutral treatment and 0.45 under the pessimistic treatment. Below a durability weight of 0.32 the model recommends PLA under every treatment; above 0.45 it recommends PETG under every treatment.

13 percentage points of the decision boundary are produced by the treatment of cells that no study has measured, not by any measurement. Sweeping the combined safety weight is more severe still: PETG reaches first rank only under the optimistic treatment and only at or above a safety weight of 0.67, which is to say that PETG can be preferred on safety grounds only when it is credited for not having been tested. No weighting makes ABS preferable to either alternative.

DOI: 10.54254/2755-2721/2026.37146

5. Discussion and limitations

Four limitations bound these results. First, the mechanical backbone of the durability and tactile-fidelity criteria is a single study [9], and that study itself varied nozzle temperature by 30 °C between the three materials, so even the one internally consistent dataset available is not free of the process confound identified in Section 3.2. Second, the product-stage safety criterion is confounded with research attention: ABS scores worst because a quantified child-exposure pathway has been established for it [8], whereas PETG scores well under the optimistic treatment because nothing has been established. Any evidence-weighted selection procedure will penalise the better-studied material, and that bias should be declared wherever such procedures are used. Third, tactile fidelity is represented by elastic modulus as a declared proxy; no measurement of tactile-feature retention after handling, cleaning or ageing was located for any of the three polymers. Fourth, fifteen sources constitute a bounded synthesis rather than a systematic review, and a larger evidence base could move the criterion scores; what it could not do is remove the missing cells, because the measurements that would fill them have not been made.

These limitations locate the central claim rather than weaken it. The published comparison literature places ABS last under every sampled weighting, can identify the durability weight at which the choice between PLA and PETG changes, and cannot resolve that choice without grade-level and service-condition information that no retained study reports.

For a practitioner the operative consequence is procedural rather than material. Where an aid is handled daily, dropped, or cleaned with warm water, the durability weight is high and PETG follows from the analysis; where the aid is a static raised-line tile kept at room temperature, the weight is low and PLA follows. In either case the filament grade, nozzle and bed temperature, layer height, infill and cleaning regime belong in the record alongside the polymer name, because the analysis shows that the polymer name alone does not determine the outcome. Such a record costs nothing to keep and is what would allow one classroom result to be compared with another.

6. Conclusion

The published literature comparing PLA, PETG and ABS cannot support a material recommendation at polymer level for children's tactile learning aids. Elastic modulus ranges for individual commercial PLA and PETG grades overlap between 1041 and 1377 MPa across two laboratories, so a comparison that names only the polymer reports a quantity smaller than its own uncontrolled variation. The safety ordering inverts twice, between emitted particle mass and per-mass particle toxicity, and again between the fabrication stage and the finished article. Under equal weights the model returns PLA first under every treatment of missing evidence, but the recommendation changes to PETG once durability carries between 0.32 and 0.45 of the total weight, and 13 percentage points of that boundary originate in cells no study has measured. ABS is excluded in all 10,626 sampled weight vectors. A defensible selection procedure must therefore specify filament grade, process parameters, service temperature and cleaning regime. Testing a finished printed aid against ISO 8124-3 or EN 71-3 remains the single most useful missing measurement. Until it exists, the safest reading of the present evidence is that the choice is a design decision to be documented, not a material property to be looked up, and to be recorded in enough detail that another school could reproduce it. The same discipline would let independent classroom results be pooled, which is at present impossible because the filament grade behind each reported outcome is unknown.

DOI: 10.54254/2755-2721/2026.37146

References

[1] Holloway, L., Marriott, K., & Butler, M. (2018). Accessible maps for the blind. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–13. https://doi.org/10.1145/3173574.3173772

[2] Wabiński, J., Śmiechowska-Petrovskij, E., & Mościcka, A. (2022). Applying height differentiation of tactile symbols to reduce the minimum horizontal distances between them on tactile maps. *PLOS ONE, 17*(2), e0264564. https://doi.org/10.1371/journal.pone.0264564

[3] Zhang, Q., Pardo, M., Rudich, Y., Kaplan-Ashiri, I., Wong, J. P. S., Davis, A. Y., Black, M. S., & Weber, R. J. (2019). Chemical composition and toxicity of particles emitted from a consumer-level 3D printer using various materials. *Environmental Science & Technology, 53*(20), 12054–12061. https://doi.org/10.1021/acs.est.9b04168

[4] Abas, M., Habib, T., Noor, S., Zimon, D., & Woźniak, J. (2023). Application of multi-criteria decision-making methods in the selection of additive manufacturing materials for solid ankle foot orthoses. *Journal of Engineering Design, 34*(8), 616–643. https://doi.org/10.1080/09544828.2023.2247859

[5] Stephens, B., Azimi, P., El Orch, Z., & Ramos, T. (2013). Ultrafine particle emissions from desktop 3D printers. *Atmospheric Environment, 79*, 334–339. https://doi.org/10.1016/j.atmosenv.2013.06.050

[6] Azimi, P., Zhao, D., Pouzet, C., Crain, N. E., & Stephens, B. (2016). Emissions of ultrafine particles and volatile organic compounds from commercially available desktop three-dimensional printers with multiple filaments. *Environmental Science & Technology, 50*(3), 1260–1268. https://doi.org/10.1021/acs.est.5b04983

[7] Mutsuga, M., Kawamura, Y., & Tanamoto, K. (2008). Migration of lactic acid, lactide and oligomers from polylactide food-contact materials. *Food Additives & Contaminants: Part A, 25*(10), 1283–1290. https://doi.org/10.1080/02652030802017529

[8] Wang, Z., Li, H., Li, T., Zhang, Q., Cai, Y., Bai, H., & Lv, Q. (2023). Application of validated migration models for the risk assessment of styrene and acrylonitrile in ABS plastic toys. *Ecotoxicology and Environmental Safety, 252*, 114570. https://doi.org/10.1016/j.ecoenv.2023.114570

[9] Ekrem, M., & Yılmaz, M. (2025). Mechanical properties of PLA, PETG, and ABS samples printed on a high-speed 3D printer. *Necmettin Erbakan Üniversitesi Fen ve Mühendislik Bilimleri Dergisi, 7*(1), 161–174. https://doi.org/10.47112/neufmbd.2025.83

[10] Vidakis, N., Petousis, M., Tzounis, L., Grammatikos, S. A., Porfyrakis, E., Maniadi, A., & Mountakis, N. (2021). Sustainable additive manufacturing: Mechanical response of polyethylene terephthalate glycol over multiple recycling processes. *Materials, 14*(5), 1162. https://doi.org/10.3390/ma14051162

[11] Sola, A., Rosa, R., & Ferrari, A. M. (2024). Environmental impact of fused filament fabrication: What is known from life cycle assessment? *Polymers, 16*(14), 1986. https://doi.org/10.3390/polym16141986

[12] Byrley, P., Boyes, W. K., Rogers, K., & Jarabek, A. M. (2021). 3D printer particle emissions: Translation to internal dose in adults and children. *Journal of Aerosol Science, 154*, 105765. https://doi.org/10.1016/j.jaerosci.2021.105765

[13] Algarni, M., & Ghazali, S. (2021). Comparative study of the sensitivity of PLA, ABS, PEEK, and PETG's mechanical properties to FDM printing process parameters. *Crystals, 11*(8), 995. https://doi.org/10.3390/cryst11080995

[14] Hsueh, M. H., Lai, C. J., Wang, S. H., Zeng, Y. S., Hsieh, C. H., Pan, C. Y., & Huang, W. C. (2021). Effect of printing parameters on the thermal and mechanical properties of 3D-printed PLA and PETG, using fused deposition modeling. *Polymers, 13*(11), 1758. https://doi.org/10.3390/polym13111758

[15] Ronca, A., Abbate, V., Redaelli, D. F., Storm, F. A., Cesaro, G., De Capitani, C., Sorrentino, A., Colombo, G., Fraschini, P., & Ambrosio, L. (2022). A comparative study for material selection in 3D printing of scoliosis back brace. *Materials, 15*(16), 5724. https://doi.org/10.3390/ma15165724