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Perceived glass-like appearance of 3D-printed prototypes: A study with evaluator-based visual assessment

Damian Dubis[1*], Jolanta Baran[1], Mateusz Zajdel[1]

[1] Institute of Technology, State University of Applied Sciences in Krosno, ul. Rynek 1, 38–400 Krosno, Poland
* Corresponding author's e-mail: damian.dubis@pans.krosno.pl

ABSTRACT

Additive manufacturing technologies, commonly known as 3D printing, have gained widespread recognition in many industries, research, and prototyping. One of the most widely used additive manufacturing methods is fused deposition modelling (FDM), which, owing to its simplicity, accessibility, and relatively low operating costs, is extensively used in industrial, educational, and hobbyist applications. Traditional methods for manufacturing transparent products, such as glassware and its substitutes, involve demanding processing conditions, limitations in shaping, and relatively high production costs. Because glass requires specialised thermal and mechanical processing, alternative methods are being explored to produce prototypes with a similar visual appearance using materials that are easier and more flexible to process. This study investigated the feasibility of producing FDM-printed prototypes with a visual appearance sufficiently similar to glass for rapid prototyping. Three filament materials – PLA, PETG, and PCTG – were evaluated, and the influence of selected printing parameters was investigated using a design of experiments (DoE) approach. The study was designed to identify a low-cost, rapidly manufacturable, and potentially disposable prototype capable of providing a sufficiently glass-like visual impression for early-stage glassware and packaging design. In this industrial context, such prototypes are intended to support decisions concerning product shape and visual appearance and are ultimately evaluated visually by designers and production personnel. Therefore, the final specimens were assessed using a visual analogue scale (VAS), with participants rating perceived transparency, colour similarity, gloss, and surface smoothness. Among the tested materials, PCTG received the highest mean ratings for perceived transparency (25.9 ± 15.8), colour similarity (39.0 ± 16.8), perceived gloss (48.7 ± 20.1), and perceived surface smoothness (32.7 ± 19.9) on a 100-point scale.

Keywords: 3D printing, glass-like properties, perceived properties, visual analogue scale, fast prototyping.

INTRODUCTION

FDM (fused deposition modelling) technology is one of the most popular methods of additive production of spatial models. It is widely used in both prototyping and unit production, as well as education and scientific research. Its most significant advantage is its availability – both in terms of equipment and materials – which results in low operating costs and versatility of applications. The FDM process involves the gradual application of plasticised thermoplastic through a heated nozzle that follows the trajectory specified in the specific file. Each new layer of plastic solidifies on the previous one until a complete spatial model is obtained (1).

Although the concept of layered manufacturing dates back to the 1940s and was first described by R.F. Housholder (2), actual development of FDM technology occurred in the 1990s (3).

The efficiency of FDM printing depends mainly on the control of processing parameters. Crucial significance holds here: the extrusion temperature, which has to be appropriately selected according to the material type; height of layer affecting reconstruction of details and smoothness of the surface; printing speed, which impacts the continuity of material; the flow rate,

determining quantity of given filament; and intensity of cooling that conditions the pace of material solidifying. Proper configuration of these parameters determines surface quality, accuracy, and ultimate utility characteristics of the model (4, 5).

The advantages of the FDM technology are: low equipment and material costs, the possibility of quick model manufacturing, and a wide range of synthetic materials, which make FDM dominant in amateur and educational environments, but it is also increasingly used in industry and research laboratories (6). Due to the ease of implementing modifications to CAD projects and the quick turnaround time for printing, this technology is excellent for supporting an iterative approach to product development, and its universality makes it an indispensable tool in modern prototyping (3).

However, the FDM method is not without its shortcomings. One of them is the segmented structure of models, which creates visible lines between layers. As a result, achieving a smooth surface is difficult. This technology requires conscious parameter optimisation to minimise defects and improve aesthetic qualities (7, 8).

Optical characteristics of the synthetics, such as translucency, clarity, gloss, and light scattering, play a crucial role in applications that require high visual quality. Synthetics used in FDM technology, PLA, PETG, and PCTG, might occur in the transparent versions, yet accomplishing a glass-like effect might demand that it meets specified conditions of processing and post–processing (9, 10).

Both material properties and print process parameters influence the transparency of FDM prints. The main technological factors include:

- Layer height – thinner layers promote better bonding of the material and reduce internal light refractions,
- Extrusion temperature – higher temperatures result in better melting and fusion of layers, which reduces phase boundaries (11, 7),
- Flow rate and printing speed – appropriate selection of these parameters allows for obtaining continuous walls and even distribution of material (5),
- Cooling – cooling too quickly can lead to internal stress and turbidity of the material (8),
- Internal structure of the polymer – materials with a lower degree of crystallinity, such as PCTG, show significantly better optical properties compared to semi-crystalline plastics such as PET or ABS. Increased transparency is associated with a homogeneous system of polymer chains that reduces light scattering at phase boundaries (12, 13).

In addition to optimising FDM process parameters, several techniques can improve the optical properties of prints. One popular approach is chemical smoothing, e.g., with acetone (for ABS), which eliminates layer boundaries and creates a shiny, smooth surface (14). For materials such as PETG or PLA, mechanical post–processing (grinding, polishing) is often used, along with transparent coatings (UV or epoxy resins), which also fill micropores and level the surface. There are advanced techniques to improve transparency – multi–stage grinding, isopropyl alcohol baths, and UV curing – that allow bringing print aesthetics closer to those of glass products. It is also worth noting that, in addition to external processes, work is underway on internal modifications of filaments, including removing particles of dyes and fillers, using raw materials with higher optical purity or doping with anti–reflective additives. Modern "glass-like" filaments are based on optimised copolymers and offer much greater material homogeneity, which significantly affects light transmission (9, 10, 13).

Glass is a material with unique optical properties that serves as an essential reference point in research on the transparency of FDM prints. As an amorphous substance without an ordered crystal structure, glass is characterised by very high transparency and a smooth surface at the microscopic level (15). For glass manufacturers, prototyping new products is a very expensive process. In some cases, glass prototypes can be replaced by 3D–printed prototypes. However, research on the 3D printing parameters necessary to achieve high-quality glass-like objects is still lacking. This paper addresses this research gap.

Last but not least, a practical application emerges from this study. In the contemporary context of sustainability, it is imperative to refrain from purchasing goods that do not fulfil an essential purpose. Therefore, it is important to design and produce well market-suitable products. From the producers' perspective, this awareness creates enhanced opportunities to design and supply products that align more precisely with consumer preferences and sustainability objectives. This approach to high–precision design will also minimise the risk of failed designs that do not meet

market requirements. This is important because ever–changing economic factors, such as rising energy prices, can lead to increased transportation and production costs as well as potentially reduce consumer demand (16). It is particularly important for energy consuming industries – as glassware production – to reduce energy consumption ex. by reducing the number of unnecessary prototypes.

The goal of the study was designed to identify a low–cost, rapidly manufacturable and potentially disposable prototype that provides a sufficiently glass–like visual impression for early-stage glassware and packaging-design activities. In this industrial use case, the prototype is intended to support shape, appearance and product-design decisions and is ultimately assessed visually by designers and production personnel. For this reason, perceived transparency, colour similarity, gloss and surface smoothness were defined a priori as the primary outcomes.

MATERIAL AND METHODS

The work focused on four types of filaments: PLA, ABS, PETG and PCTG, which differ in mechanical, thermal and optical properties. Each of these materials is characterised by different levels of transparency, susceptibility to deformation and temperature requirements, which directly influenced the optical quality of the obtained prints.

Polylactic acid (PLA) is a biodegradable polyester acquired from renewable resources such as corn starch, sucrose, or sugarcane. In the FDM technology, such material is considered the easiest to use – it is popular with both amateurs and professionals due to its low susceptibility to deformation, high layer adhesion, and aesthetic print appearance. PLA is characterised by a relatively low processing temperature (180–220 °C), allowing printing without a heating chamber or heated table. The glass transition temperature of this material is around 60°C, and the melting temperature is in the 150–180 °C range. In terms of mechanical properties, PLA offers tensile strength of about 40–70 MPa, a modulus of elasticity of 3–4 GPa, and a density of 1.21–1.25 g/cm³. Low emission of volatile organic compounds during the printing process and their wide availability make PLA a perfect material for educational, hobby, and prototype purposes (17–19).

Polyethylene terephthalate glycol (PETG) is one of the most commonly used FDM technology materials, connecting the ease of PLA printing with the mechanical durability of technical materials. It is an amorphous material, which allows for its transparency and aesthetic appearance of its surface, especially in the transparent versions. In terms of technological properties, PETG is characterised by an extrusion temperature of about 210–235 °C (most commonly 230°C) and the required temperature of the table around 50 to 80 °C. Glass transition temperature for this material is about 75–80 °C and the heat deflection temperature of 62–68 °C, depending on the load (17). The density of the material is in the 1.24–1.27 g/cm³ range (13). PETG offers tensile strength of around 50–55 MPa, Young's modulus of about 3–3.5 GPa and elongation at break up to 35%, which in turn allows for high impact resistance (20). Additionally, this material exhibits high chemical resistance and low moisture absorption, which is why it performs well under outdoor conditions and withstands contact with chemicals (13).

Polycyclohexylendimethylene terephthalate glycol–modified (PCTG) is a copolymer and a modified version of PETG, enriched with additives that improve its mechanical and optical properties. This material combines high mechanical resistance with high transparency, making it a very interesting choice for the research focused on the visual quality of 3D prints. The technological properties of PCTG are characterised by thermal stability and good interlayer adhesion, yet they strongly depend on the layer's height and orientation (21). The recommended extrusion temperature is 250–270 °C, and the print bed temperature is 90–110 °C. The material does not require an enclosed build chamber, making it easier to process on a standard FDM printer. PCTG has high impulse resistance – up to 90 kJ/m² – which significantly exceeds typical values for PETG. The heat deflection temperature (HDT) coefficient reaches approximately 76 °C. The density of PCTG ranges from 1.22 to 1.24 g/cm³. Transparent variants – such as pure TR – offer high optical clarity and are certified for food contact (BPA free), making the material suitable for applications in the food and medical industries (Marcinkowska, 2023a).

Acrylonitrile-butadiene-styrene (ABS) is a plastic with high mechanical strength and thermal resistance, widely used in FDM technology. It is

produced by copolymerisation of three monomers: acrylonitrile, butadiene, and styrene, which combine hardness, elasticity and impulse resistance. In terms of technological parameters, ABS requires a relatively high printing temperature – 230 to 250 °C – and a print bed at 90–110 °C. The glass transition temperature of this material is approximately 105 °C, and the HDT temperature reaches 91 °C. The density of the material ranges from 1.05 to 1.10 g/cm³. ABS is characterised by good mechanical strength: tensile strength of around 30–40 MPa and a modulus of elasticity of 1.8–3.2 GPa. The material also offers high impact resistance (up to 70 kJ/m² in "high–impact" versions) and good chemical resistance to acids, bases, and oils. What is important, ABS can undergo chemical smoothing (e.g. with acetone vapour), which allows for the creation of smooth and glossy surfaces (22, 23).

In the present study, glass serves as a reference material point relative to thermoplastics. This research is interdisciplinary – it combines 3D printing technology with visual analysis and materials aesthetics, enabling the determination of the limits of reproducing the visual quality of glass in an additive manufacturing environment (Zhang et al., 2025).

It was assumed that the ideal glass–like printout should reproduce as accurately as possible:

- high light transmission (without fogging and refraction),
- aesthetic gloss and uniform surface,
- no visible layers and geometric distortions.

Before printing, it was necessary to add a reference image that allowed the exact shape of the cup to be mapped (Figure 1). Blender software was used in the experiment.

The finished model was then compared visually with a real glass to assess the conformance of the shape qualitatively (Figure 2).

Before proceeding to the proper experimental prints, it was necessary to prepare the 3D printing environment. This included preparing the materials, configuring the PrusaSlicer software, and adjusting the Prusa printer parameters. The first stage was filament drying – a key technological process for print surface quality. Materials such as PLA, PETG, or PCTG are hygroscopic – they absorb moisture from the environment. Drying was carried out in a dedicated heated container for a minimum of 8 hours at 50 to 65 °C, in accordance with the manufacturer's recommendations.

Preliminary research was conducted to identify the materials best suited for further study. Then, appropriate tests were performed using the design of experiments (DoE) method. Parameters such as head temperature, print speed, layer height, and flow rate were changed. The aim was to determine a set of parameters optimal from the point of view of visual effects, including transparency, smoothness, colour, and gloss. The visual analogue scale (VAS) method was also used in the study. The selection of these methods was driven by the need to combine quantitative (statistical) analysis with subjective assessment, reflecting end users' perception.

DoE is a set of statistical techniques used for planning, conducting, and analysing experiments to maximise the amount of information obtained while minimising the number of trials. In the context of research on FDM 3D printing, DoE enables analysis of the influence of multiple process parameters on selected final print properties, such as optical, surface, or mechanical quality (Bower, 2024). This method enabled the experiment to be designed systematically and optimally, allowing the assessment of the impact of technological variables on aesthetic properties. Studies have demonstrated the effectiveness of DOE in analysing the influence of parameters on mechanical strength and dimensional accuracy, while other works have confirmed its usefulness in examining parameters affecting surface appearance (Murali et al., 2025; Zharylkassyn et al., 2021).

The method used in this study allowed for the collection of qualitative data through visual assessment of four properties of printed samples: perceived transparency, perceived colour similarity, perceived gloss, perceived surface smoothness. Those visual attributes were treated as perceptual constructs rather than as instrumentally measured material properties. Accordingly, the term perceived transparency refers to the observer's subjective impression of the ability to see through the specimen, whereas perceived optical clarity describes the degree to which details of objects viewed through the specimen remain distinct and undistorted. Translucency refers to the visual condition in which light passes through the material but object details cannot be clearly resolved, while perceived haze denotes a cloudy or milky appearance that reduces visual contrast. Perceived gloss refers to the visual impression produced by light reflected



Figure 1. Photo of the glass tumbler added to 3D design software

from the specimen surface. Finally, perceived surface smoothness describes the visual impression of surface uniformity and the absence of clearly visible layer lines and local irregularities. These perceptual descriptors should not be interpreted as equivalents of instrumentally measured luminous transmittance, haze, specular gloss, or surface–roughness parameters.

Participants were asked to indicate the intensity of each characteristic by marking the appropriate point on a 100 mm long line, ranging from "none" (0) to "maximum intensity" (100). The models made from individual filaments were subjected to subjective visual assessment by 20 study participants. Each feature was evaluated independently on a scale of 0 to 10, where 0 indicated the absence of the feature (e.g., a completely matte surface) and 10 its maximum quality (e.g., a glassy gloss). The ratings were recorded on individual sheets and then averaged (McCormack et al., 1988) (Lee, 2016).

RESULTS

Based on the visual assessment of the samples produced during the preliminary tests, the PLA, PETG, and PCTG filaments received positive evaluations. These materials demonstrated at least a partial ability to form translucent structures with the appropriate print settings. Based on preliminary selection of materials and printing parameters, the primary studies were conducted using the DOE method. The aim of this stage was to identify the most effective combinations of printing parameters that achieve maximum transparency for 3D structures created using the FDM method.

The experiment considered three independent variables:

- printhead temperature: two levels,
- print speed: two levels,
- flow rate (amount of material extruded): two levels.



Figure 2. The finished 3D printable model compared to the original glass product

Eight samples were prepared for each material, covering all parameter combinations (complete 2^3 plan). Each sample was visually evaluated and assigned a value on a scale of 1 to 10, where:

- 1 indicates no transparency (matte surface, defects),
- 10 indicates maximum possible transparency in the context of FDM technology.

A full DoE matrix has been prepared, describing factor levels, coding, and interactions between them (Table 1).

As part of the experimental research, the influence of key printing parameters on the visual quality of PLA filament prints was analysed. The best results for PLA were obtained in sample 3 (180 °C, 60 mm/s, 100% flow rate), which received a score of 10. High printing speed at low temperature most likely limits material overheating, reducing the risk of scorching and discoloration. In contrast, increasing the temperature to 220 °C (samples 5–8) resulted in poorer quality – the prints had darker, more milky areas, which led to low scores of 3–4.

PETG achieved the best result in sample 2 (220 °C, 15 mm/s, 102%) – score 10. At a moderate temperature and very low speed, it was possible to evenly plasticise the filament and apply the layer precisely, resulting in good visual quality.

The PCTG filament showed the highest tolerance to changes in printing parameters. Sample 1 (250 °C, 15 mm/s, 100%) – score 9, and 4 (250 °C, 60 mm/s, 102%) – score 10. Both combinations differed significantly in speed and flow rate, suggesting that this material performs well across a wide range of conditions, provided the temperature is properly maintained.

As a supplement to the qualitative research, a subjective evaluation of the 3D prints was carried out using the visual analogue scale (VAS) method. This assessment enabled comparison of various aspects of the visual quality of 3D

Table 1. DoE matrix

Material	Order	Code	A – Temp. [°C]	B – Speed [mm/s]	C – Flow rate [%]	A	B	C	AB	AC	BC	ABC	Grade
PLA	1	321	180.0	15	100	–1	–1	–1	1	1	1	–1	8
PLA	2	685	180.0	15	102	–1	–1	1	1	–1	–1	1	9
PLA	3	496	180.0	60	100	–1	1	–1	–1	1	–1	1	10
PLA	4	512	180.0	60	102	–1	1	1	–1	–1	1	–1	8
PLA	5	278	220.0	15	100	1	–1	–1	–1	–1	1	1	4
PLA	6	854	220.0	15	102	1	–1	1	–1	1	–1	–1	3
PLA	7	951	220.0	60	100	1	1	–1	1	–1	–1	–1	4
PLA	8	259	220.0	60	102	1	1	1	1	1	1	1	3
PETG	1	486	2200	15	100	–1	–1	–1	1	1	1	–1	4
PETG	2	531	220.0	15	102	–1	–1	1	1	–1	–1	1	10
PETG	3	248	220.0	60	100	–1	1	–1	–1	1	–1	1	9
PETG	4	975	220.0	60	102	–1	1	1	–1	–1	1	–1	8
PETG	5	412	245.0	15	100	1	–1	–1	–1	–1	1	1	1
PETG	6	111	245.0	15	102	1	–1	1	–1	1	–1	–1	1
PETG	7	845	245.0	60	100	1	1	–1	1	–1	–1	–1	1
PETG	8	774	245.0	60	102	1	1	1	1	1	1	1	1
PCTG	1	393	250.0	15	100	–1	–1	–1	1	1	1	–1	9
PCTG	2	968	250.0	15	102	–1	–1	1	1	–1	–1	1	8
PCTG	3	855	250.0	60	100	–1	1	–1	–1	1	–1	1	7
PCTG	4	741	250.0	60	102	–1	1	1	–1	–1	1	–1	10
PCTG	5	797	270.0	15	100	1	–1	–1	–1	–1	1	1	3
PCTG	6	621	270.0	15	102	1	–1	1	–1	1	–1	–1	2
PCTG	7	645	270.0	60	100	1	1	–1	1	–1	–1	–1	2
PCTG	8	882	270.0	60	102	1	1	1	1	1	1	1	3

models produced from individual filaments. Twenty participants took part in the test, independently evaluating the samples for perceived transparency, perceived colour, perceived gloss, and perceived surface smoothness. Three samples were examined – those that had obtained the highest scores in the previous stage (PLA – sample 3, PETG – sample 2, and PCT – sample 4). A sample made of pure, colourless glass was used as a reference (Figure 3).

At the beginning of the experiment, the samples were observed under a microscope. This allowed for a more detailed examination of the surfaces before conducting a VAS assessment. A ZEISS Stemi 508 stereoscopic microscope with an Axiocam 105 colour module was used for the research. As a reference mode, a glass goblet was used, whose aesthetic and optical features served as a basis for evaluating the samples produced through the 3D printing process. All samples were observed at 10x magnification and at 50x, against a black background and using an LED light illuminating the sample from above.

The surface of the glass sample was mostly smooth and transparent. Only minor imperfections were observed, including a few isolated mouldmarks (Figure 4).

Next, all the printed samples were examined. Based just on microscopic examination, it occurred that the sample made of PCTG has the best visual properties (Figure 5). The surface appeared the glossiest and shiniest, and the 3D printed layers were less visible than those of PETG (Figure 6) and PLA (Figure 7).

The statistical analysis of the results was performed using Statistica 13.3. The significance level of $\alpha=0.05$ has been applied.

The results show that the best transparency was achieved by the samples made from PCT-G, which reached an average rating of 25.9 ± 15.8.



Figure 3. Finished 3D printed samples before VAS evaluation

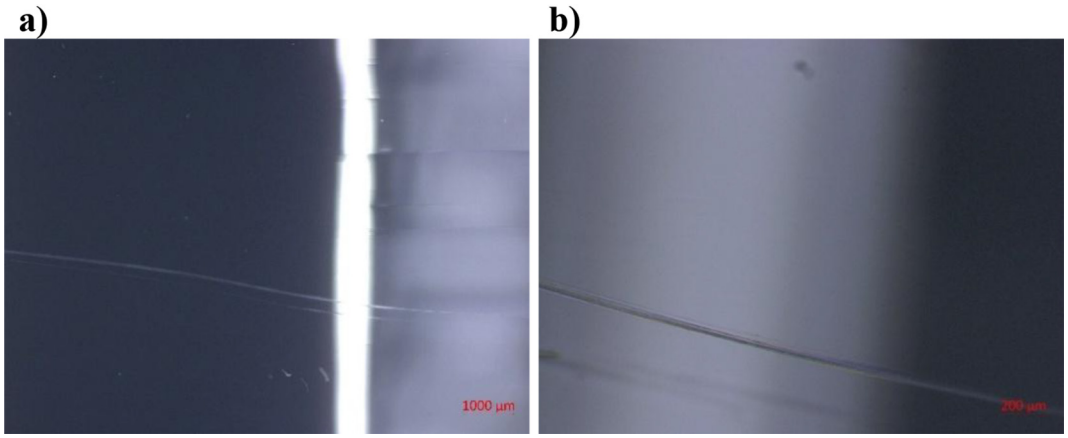


Figure 4. Glass reference sample's surface fragment with minor isolated mouldmarks: a) 10× magnification, b) 50× magnification

Although these values are not high on an absolute scale, they are the highest relative to the other materials (Figure 8).

The highest average perceived colour rating was achieved by the PCTG material, which obtained a rating of 39.0 ± 16.8. Respondents described the colour of the samples as the closest to natural – semi–transparent, without discolorations or irregularities. This is consistent with the manufacturer's claims about the material's high optical quality (Figure 9).

In the perceived gloss category, PCTG once again received the highest rating – an average of 48.7 ± 20.1. The samples made from this material were perceived as the most uniform, and their surface achieved a distinct gloss even with basic printing parameters. In several cases, respondents described the surface as resembling high–quality plastic (Figure 10).

For smoothness, the highest rating was given to the PCTG material, which achieved an average of 32.7 ± 19.9. Although this was not a high value in absolute terms, respondents unanimously described the samples as relatively smooth and homogeneous, especially at lower layer heights and appropriate flow rates. Prints from this material showed less visible transitions between layers (Figure 11).

Because the same 20 evaluators assessed all three materials, the observations were treated as repeated measures. For each perceptual attribute (perceived transparency, perceived colour similarity, perceived gloss, and perceived surface smoothness), differences between PLA, PCTG, and PETG were analysed using a one–way repeated–measures analysis of variance (RM–ANOVA). The significance level was set at $\alpha = 0.05$. Where the ANOVA indicated a significant material effect, paired post–hoc comparisons were performed with Holm correction for multiple testing. Effect size was reported as partial eta squared (partial η^2). Mean values and standard deviation for all the parameters and materials are summarised in Table 2. ANOVA results are summarised in Table 3.

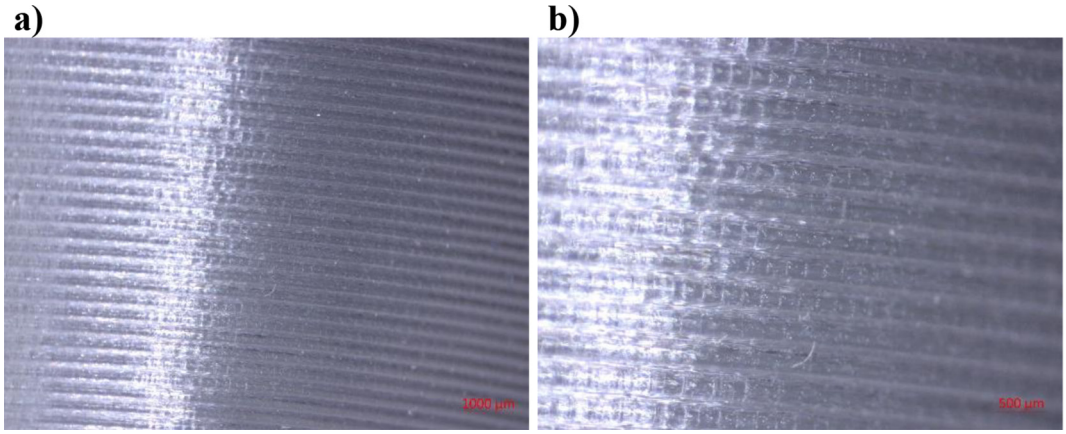


Figure 5. Fragment of the sample surface made of PCTG: a) 10× magnification, b) 50× magnification

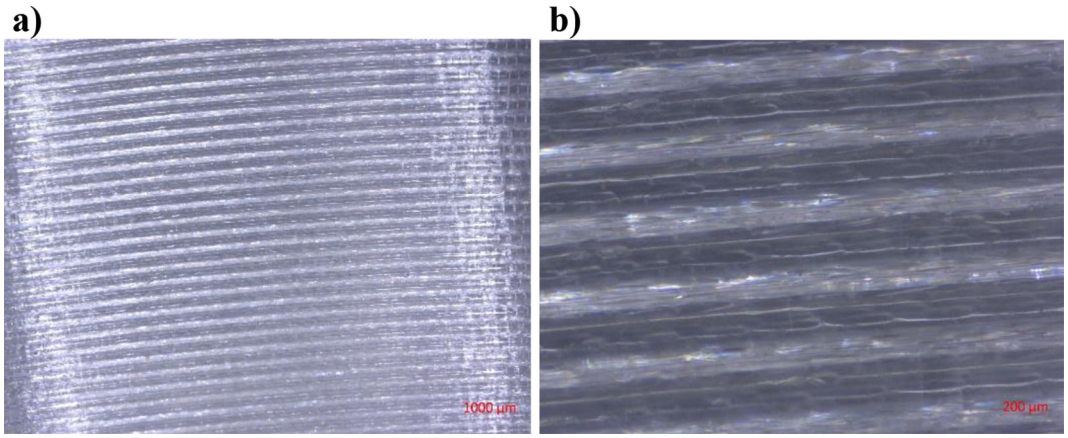


Figure 6. Fragment of the sample surface made of PETG: a) 10× magnification, b) 50× magnification

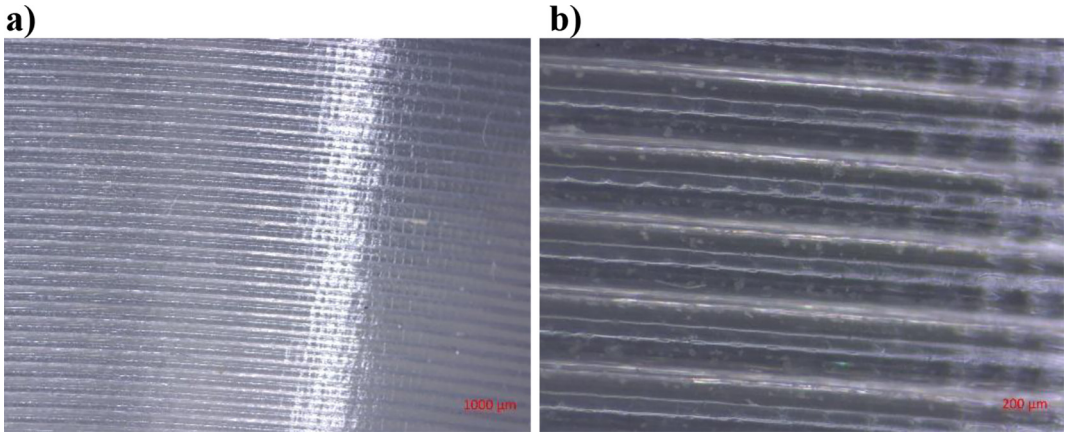


Figure 7. Fragment of the sample surface made of PLA: a) 10× magnification, b) 50× magnification

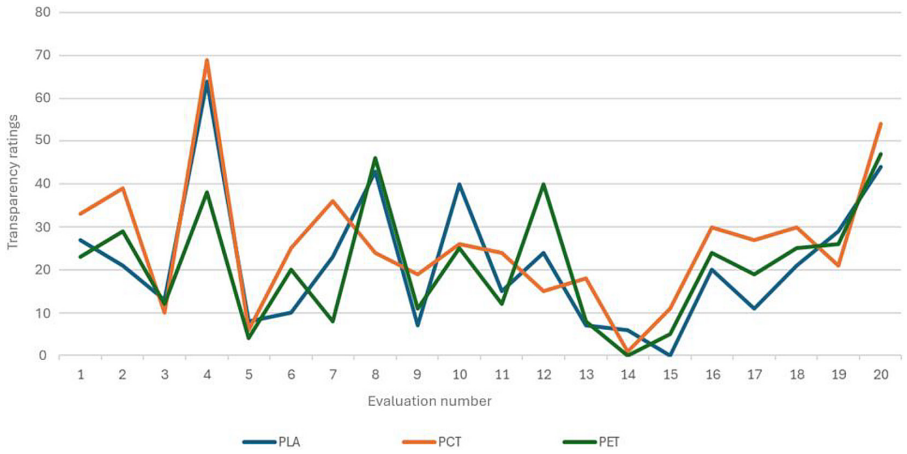


Figure 8. Perceived transparency ratings of printed samples by 20 evaluators

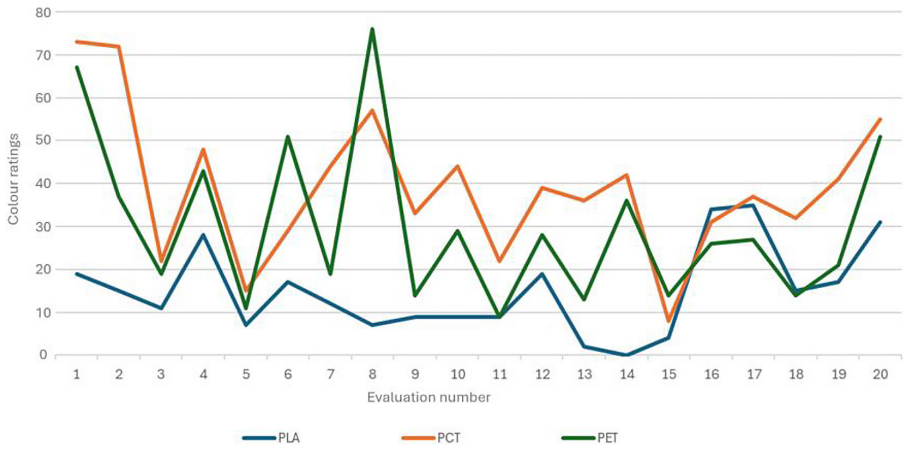


Figure 9. Perceived colour ratings of printed samples by 20 evaluators

The average level of similarity between the perceived transparency of the tested products and the transparency of the reference product ranges from 21 to 26 (on a 100–point scale). Therefore, it should be concluded that, in terms of this characteristic, the reference product differs significantly from the tested products (Table 2). The evaluation of this characteristic did not reveal any statistically significant differences between the tested samples (Table 3).

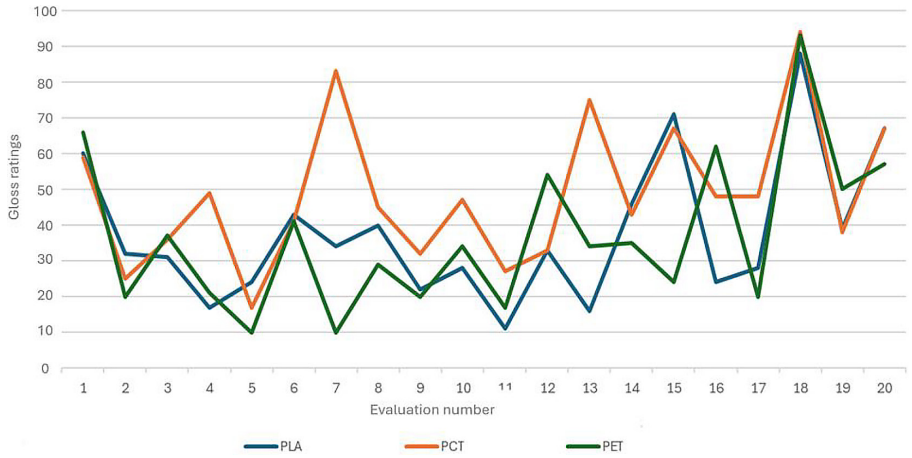


Figure 10. Perceived surface gloss ratings of printed samples by 20 evaluators

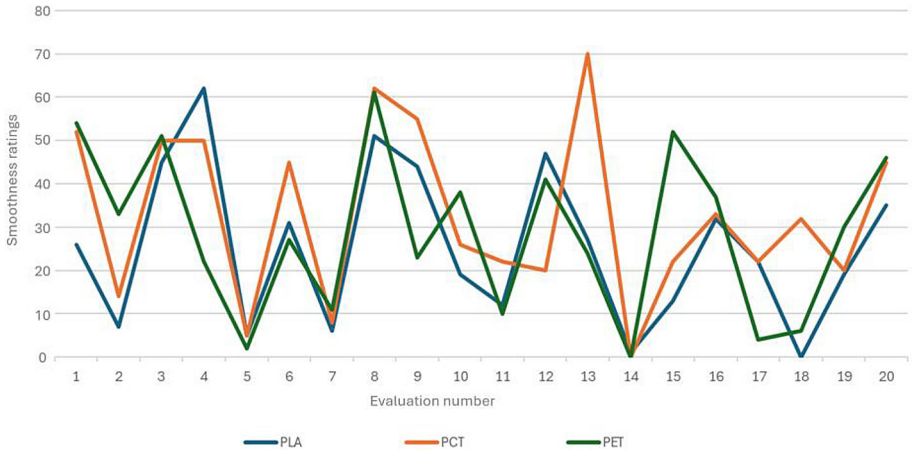


Figure 11. Perceived surface smoothness ratings of printed samples by 20 evaluators

The average level of similarity between the colour of the examined products and the colour of the reference product ranges from 15 to 39 (on a 100–point scale), so it must be concluded that, in terms of this characteristic, the reference product differs significantly from the examined products. The assessment of this parameter revealed significant differences between the products tested ($p<0.05$).

The average level of similarity between the perceived gloss of the examined products and the gloss of the reference product ranges from 37 to 49 (on a 100–point scale), so it must be concluded that, in terms of this feature, the reference product differs significantly from the examined products. The assessment of this feature revealed significant differences between the products tested ($p<0.05$). The similarity of the gloss of the PCT product to the gloss of the reference standard was rated higher than that of the other products (Table 3).

In terms of smoothness, the highest rating was given to the PCT-G material, which achieved an average of 32.7 ± 19.9. Although this was not a high value in absolute terms, respondents unanimously described the samples as relatively smooth and homogeneous, especially at lower layer heights and appropriate flow rates. Prints from this material showed less visible transitions between layers. Yet, no statistical differences between materials have been discovered (Table 3).

A significant effect of material was observed for perceived colour similarity, $F(2.38) = 20.73$, $p < 0.001$, partial $\eta^2 = 0.522$. Holm–adjusted pairwise comparisons showed that PCTG received significantly higher ratings than both PLA (adjusted $p < 0.001$) and PETG (adjusted $p = 0.010$). PETG was also rated significantly higher than PLA (adjusted $p = 0.004$). Post-hoc results with Holm-adjustments are summarised in Tables 4 and 5.

Material significantly affected perceived gloss, $F(2.38) = 4.66$, $p = 0.016$, partial $\eta^2 =$

Table 2. Mean values and standard deviation for all the parameters and materials

Parameter	PLA	PCTG	PETG
Perceived transparency	21.65 ± 16.02	25.90 ± 15.82	21.10 ± 13.91
Perceived colour similarity	15.00 ± 10.26	39.00 ± 16.77	30.25 ± 18.96
Perceived gloss	37.70 ± 20.04	48.70 ± 20.06	36.70 ± 21.41
Perceived surface smoothness	25.20 ± 18.00	32.65 ± 19.91	28.60 ± 18.89

0.197. PCTG received the highest mean gloss rating (48.7 ± 20.1). Holm–adjusted pairwise comparisons showed a significant difference between PCTG and PLA (adjusted p = 0.044), whereas the difference between PCTG and PETG narrowly failed to reach the 0.05 significance level (adjusted p = 0.051). PLA and PETG did not differ significantly (adjusted p = 0.805).

Although PCTG received the highest mean perceived–smoothness rating (32.7 ± 19.9), the repeated–measures ANOVA did not reveal a significant effect of material, $F(2.38) = 1.84$, $p = 0.173$, partial $\eta^2 = 0.088$.

PCTG received the highest mean ratings for all four perceptual attributes. However, the statistical evidence differed between attributes. A strong and consistent material effect was observed for perceived colour similarity, while the parametric analysis also indicated an effect on perceived gloss. No significant material effect was detected by repeated–measures ANOVA for perceived transparency or perceived surface smoothness. Therefore, the higher mean ratings of PCTG for these attributes should be interpreted descriptively rather than as evidence of statistically demonstrated superiority.

DISCUSSION

Despite achieving satisfactory results in some categories, several factors still limit the ability to obtain the glass effect using the FDM printing method. The most important include:

- the visibility of layers resulting from the operating principle of FDM technology,
- the optical limitations of materials (light transmittance, impurities),
- uneven cooling and material flow,

Table 3. Summary of ANOVA results

Parameter	F	p value	partial η^2	Conclusion
Perceived transparency	2.211	0.1235	0.104	No significant difference
Perceived colour similarity	20.73	<0.000001	0.522	Significant difference
Perceived gloss	4.655	0.0156	0.197	Significant difference
Perceived surface smoothness	1.841	0.1725	0.088	No significant difference

Table 4. Post–hoc results for perceived colour similarity

Materials	difference between means	p value	adjusted p-value (Holm)
PLA – PCTG	−24.00	0.0000056	0.000017
PLA – PETG	−15.25	0.00209	0.00419
PCTG – PETG	8.75	0.01033	0.01033

Table 5. Post–hoc results for perceived gloss

Materials	Difference between means	p value	Adjusted p-value (Holm)
PLA – PCTG	−11.0	0.0148	0.0443
PLA – PETG	1	0.8045	0.8045
PCTG – PETG	12	0.0253	0.0506

- difficulties in maintaining an entirely uniform Surface without post–processing,

Considering the above, it is worth noting the following directions for future work:

- the use of additional chemical or thermal treatment to smooth the surface.
- use of dedicated optical filaments (e.g., PMMA or special "glass effect" PETG),
- use of SLA or DLP technology as a comparison to achieve better visual effects,
- use of automated measurement systems (e.g., spectrophotometric) to judge light transmittance and colour.

Despite the application of these methods, achieving complete transparency comparable to glass remains difficult in FDM technology. The main obstacle is the characteristic layered structure and the presence of microgaps between strips of material, which lead to light scattering and refraction (8). Another significant limitation is the quality of the filament, its purity, moisture, or presence of fillers or dyes may noticeably degrade the visual effects (12, 13). For these reasons, the literature highlights that transparency in FDM printing should be a relative property, optimisable to a limited degree, but not comparable to the properties of conventional glass (15, 8). The use of combined techniques, such as careful material selection, precise printer calibration, and careful post–processing, offers a realistic chance of obtaining high–quality prints suitable for prototyping or educational purposes. PETG was investigated over a printing temperature range of 210–255 °C using micro-computed tomography and tensile testing. The study shows that the mechanical properties of the printed parts are strongly related to their microstructure, defects, and processing temperature (24).

Although Macek et al. investigated fatigue fracture surfaces rather than optical appearance, their entire–surface approach demonstrates the value of linking quantitative surface descriptors with functional performance (25). By analogy, perceived glass–likeness in prototypes may be interpreted together with quantitative descriptors such as layer–line visibility, defect–area fraction, texture uniformity, and, where height–resolved measurements are available, areal surface–topography parameters. Such an approach would reduce the risk of drawing conclusions from selectively chosen microscopic fields and would provide a physical context for evaluator–based ratings. Another publication compares PETG with PLA and ABS and examines the effect of raster orientation. It is a useful source for emphasising that the properties of printed parts are not necessarily equivalent to those of the raw material (26, 27).

CONCLUSIONS

Based on the research and analyses, the objective was partially achieved. In practice, all the materials used do not allow for very high glass-like performance due to their structure and surface properties. Although it was not possible to obtain fully transparent models that would imitate glass in the literal sense, PCTG can be used, with some limitations, for quick prototyping of glass products, especially in situations where disposable samples need to be quickly manufactured. The results also demonstrated that, through an appropriate selection of materials and printing parameters, it is possible to improve the optical properties of the sample.

It is worth noting that the VAS method proved to be an effective tool for assessing properties that are difficult to quantify. The study enabled the identification of the most promising materials and process settings. It also highlighted the potential of a design–research methodology in use with DoE and VAS. The study does not demonstrate optical equivalence to glass or general superiority of PCTG outside the investigated printer, geometry, filament grade, and processing ranges. Yet, the obtained knowledge provides a foundation for further experiments. It may serve as a starting point for developing technical elements produced for the purpose of fast prototyping.

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