Original scientific paper

Exploration of biodegradable materials for a digitally printed fashion embellishments

ABSTRACT

Initially utilized in aerospace and medical industries, 3D printing has emerged as revolutionary technology with significant potential in transforming garment creation that previously unattainable through traditional manufacturing. The integration of biodegradable materials in 3D printing represents a promising approach in addressing the environmental challenges posed by conventional plastic-based printing technologies. This study explores biodegradable materials—Polyterra PLA, Esun PLA+, and bio resin—for producing digitally printed sustainable fashion embellishments. Through a mixed method approach involving practical experimentations, a flower-shaped embellishment prototype was made and painted for application on garment. By addressing the limitations of biodegradable materials and demonstrating their potential in high-fashion applications, this study contributes to the advancement of 3D printing by optimising biodegradable materials for a more sustainable and creative design potential for the fashion industry.

KEY WORDS
3D printing, fashion embellishments, biodegradable material, sustainable

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Introduction

Technological advancements have continuously shaped various industries, with the fashion sector being no exception. Over the past few decades, innovations such as computer-aided design (CAD), augmented reality (AR), and smart textiles have revolutionized the industry, enabling new creative possibilities, efficiency, and consumer engagement. CAD software has streamlined the design process by enabling the creation of precise digital prototypes, reducing the time and cost associated with physical mock-ups (Adediran et al., 2024; RS Design Spark, n.d.). Introduced in 1987, CAD is widely used for creating garment components, patterns, and simulations, significantly enhancing efficiency and accuracy (Singh, 2021).

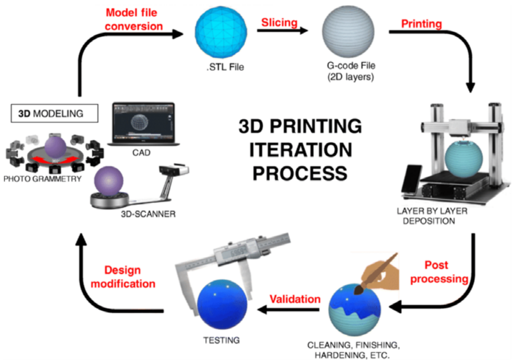
Smart textiles, another breakthrough, incorporate sensors and adaptive materials that interact dynamically with the wearer, offering functionalities like temperature regulation and health monitoring (Ruckdashel, Venkataraman & Park, 2021).

Among these breakthroughs, three-dimensional (3D) printing stands out as a revolutionary technology with immense potential to redefine garment creation.

Initially utilized in aerospace and medical industries, 3D printing is now gaining prominence in fashion, offering designers the ability to create intricate, customized pieces previously unattainable through traditional manufacturing.

Despite its benefits of allowing for flexible designs with high precision (Gudaitiene, Minkus & Darulis, 2025), 3D printing faces challenges especially in fashion industry. High production costs, long printing times, and material limitations, such as brittleness and lack of flexibility, hinder its widespread adoption (Xiao & Kan, 2022).

Moreover, the environmental sustainability of 3D printing materials, typically plastic-based, raises concerns (Jandyal et al., 2022). Figure 1 below shows the 3D printing iteration process.



» **Figure 1:** *3D printing iteration process (Ambrosi & Bonanni, 2021)*

3D printing has emerged as a revolutionary technology in fashion, enabling intricate designs, new innovative fabrications, personalized products, and for high fashion applications (Olawumi et al., 2023; Sheikh et al., 2020; Sun & Zhao, 2017). By constructing objects layer by layer, 3D printing facilitates the creation of complex geometries and reduces material waste (Shahrubudin, Lee & Ramlan, 2019). This technology, initially commercialized in 1980, has expanded across industries, with the global market for 3D printing expected to grow by 25% annually until 2030 (Yoo, 2025).

Fashion applications range from haute couture to accessories, with designers like Iris Van Herpen and Daniel Peleg pioneering its use. Van Herpen's experimental designs and Peleg's fully 3D-printed garments highlight the potential of this technology to push creative boundaries (Deabler, 2017; Holgate, 2016). Similarly, Koerner's innovative use of 3D printing in films like Black Panther highlighted the medium's versatility and aesthetic appeal (Guimapang, 2019).

In Indonesia, 3D printing is still in its early stages due to limited access to advanced machines. Designers like Tex Saverio and DIBBA have showcased its potential by combining 3D-printed elements with traditional techniques (Idea3D, 2015; Kuswanto et al., 2017). Technological advancements like CAD, smart textiles, and 3D printing are reshaping fashion, offering new possibilities for design and production. While challenges remain, ongoing research into sustainable materials and innovative applications promises a more efficient and environmentally conscious future for the industry.

While 3D printing has enabled rapid prototyping, customization, and waste reduction (Olawumi et al., 2023), its reliance on non-biodegradable materials, such as thermoplastics and resins, presents significant environmental challenges. Plastics, the primary materials for 3D printing, contribute substantially to global waste, with over 400 million tons generated annually and projections indicating continued growth (Dueñas-Moreno et al., 2023; IUCN, 2024; Rodríguez-Hernández et al., 2020). Improper disposal exacerbates this issue, polluting ecosystems and posing risks to biodiversity and human health (Filamatrix Staff, 2024; Oladapo et al., 2023). The rise of sustainability in fashion demands alternatives that align with environmentally conscious practices.

Biodegradable materials, such as polylactic acid (PLA) and bio-resins, have emerged as promising substitutes, capable of decomposing under certain conditions and reducing the ecological footprint of 3D-printed products (Byjus, 2018; Oladapo et al., 2023). These materials are derived from renewable resources and have a lower environmental impact compared to non-biodegradable materials, such as petroleum-based plastics (Subramani et al., 2024). However, their integration into fashion faces significant hurdles, including brittleness, limited heat resistance, and higher costs. Additionally, existing research on the use of biodegradable materials in 3D printing for fashion remains sparse, with most studies focusing on technical applications rather than fashion, leaving critical questions about their viability and optimization unanswered. Despite these advancements, the industry's reliance on non-biodegradable materials limits its sustainability. Efforts to recycle 3D printing waste have also been hindered by inconsistent material quality and the complexities of multi-material recycling. This study addresses these gaps by exploring how biodegradable materials can be leveraged to create durable, aesthetically appealing, and sustainable fashion garments.

To tackle the challenges of using biodegradable materials in 3D-printed fashion, this research adopts a multidisciplinary methodology combining material science, design experimentation, and environmental assessment. The approach begins with a comprehensive evaluation of biodegradable filaments and bio-resins, focusing on their mechanical properties, thermal stability, and biodegradability. Laboratory testing will identify the limitations and opportunities of these materials, providing insights into their suitability for high-fashion applications.

3D Printing Materials

The selection of materials for 3D printing plays a pivotal role in determining the quality, sustainability, and functionality of printed objects. Among the various materials used in 3D printing, filaments such as PLA and ABS, as well as liquid resins, stand out. PLA, or polylactic acid, is a biodegradable polymer derived from renewable resources like corn starch and sugarcane. It is favoured for its affordability, ease of use, and environmental benefits (Conniff & Tewolde, 2022). PLA is especially relevant to this research as it aligns with the focus on sustainability and biodegradability. While PLA's properties include a low melting point and user-friendly printing characteristics, its brittleness and limited thermal resistance pose challenges for applications requiring durability (Polygenis, 2023).

In contrast, ABS is a petroleum-based thermoplastic known for its strength, impact resistance, and suitability for high-performance applications. However, its environmental drawbacks, such as non-biodegradability and the release of toxic fumes during printing, make it less desirable for sustainable initiatives (Khosravani & Reinicke, 2020; Printerra, 2023). Liquid resins, used primarily in SLA machines, offer high resolution and smooth surface finishes but are not biodegradable and pose environmental and health risks due to their toxic nature (Madeline, 2023).

The Fused Deposition Modelling (FDM) machine is widely used for 3D printing for its affordability, user friendliness, and compatibility with thermoplastic filaments like PLA (Xiao & Kan, 2022). It is one of the widely used additive technology using digital 3D CAD model for the creation of prototype. The FDM process involves heating the filament to its melting point and extruding it through a nozzle to build objects layer by layer (Warnier et al., 2014), where printing accuracy is influenced by key parameters such as raster width, nozzle diameter (typically 0.2–0.6 mm), print speed, temperature, raster angle, and layer thickness (Žarko et al., 2017). The standard workflow beginning with CAD modelling, followed by STL export, slicing, printing, and finishing aligns well with the design-to-prototype sequence required in this project. However, these same parameters also introduce technical limitations, particularly when printing intricate forms or thin decorative elements (Gudaitiene, Minkus & Darulis, 2025).

Fine details below 2 mm, for example, are susceptible to deformation, uneven edges, or surface inconsistencies depending on the selected print settings. While FDM machines are not capable of achieving the high resolution of SLA or SLS machines, their low cost and accessibility make them ideal for exploratory research and prototyping in fashion applications.

Moreover, the simplicity of FDM technology allows experimentation with material modifications and the development of innovative designs. Despite its relatively rough surface finishes and slower printing speeds compared to other technologies, the FDM machine's ability to produce functional and cost-effective prototypes supports its selection for this study. The method used in this study is grounded in recognized additive manufacturing practices while acknowledging limitations that influenced the final prototype quality.

The success of an FDM print relies not only on the design of the model but also on the careful selection of printing parameters that directly influence structural accuracy and surface quality. Poorly prepared models or inappropriate parameter choices can result in defects such as uneven surfaces, tearing during printing, or dimensional inaccuracies caused by internal stresses in the material. Similarly, layer thickness and raster width significantly affect the smoothness and resolution of the printed surface; thinner layers and narrower raster widths produce finer, more detailed finishes, whereas thicker layers create visible stepping and rougher textures (Gudaitiene, Minkus & Darulis, 2025). Incorporating these considerations is essential for ensuring the reliability and reproducibility of 3D-printed fashion embellishments.

Biodegradable materials, particularly PLA, are gaining traction as an eco-friendly alternative to traditional 3D printing materials. PLA's biodegradability stems from its composition of renewable sources and its ability to decompose under industrial composting conditions (EDI, n.d.). However, PLA's mechanical properties, such as low tensile strength and brittleness, limit its use in applications requiring high durability (Subramani et al., 2024). Additionally, PLA's low melting point restricts its suitability for high-temperature environments.

Although biodegradable films have a high potential as a sustainable approach to 3D Printing, they have several challenges that need to be addressed to identify the full potential of the materials. There must be deeper research and development to improve the cost, strength, and properties. Despite the challenges in using biodegradable materials, the demand for sustainable materials and 3D Printing technology has risen in recent years (Subramani et al., 2024). The flexibility of the design and high customization of biodegradable materials create new possibilities for sustainable production and design processes while addressing the rising issue of plastic pollution. The adoption of biodegradable materials in 3D printing also addresses the growing concern of plastic pollution. Failed prints and support structures contribute significantly to 3D printing waste. PLA's biodegradability allows for reduced environmental impact, as it can decompose more efficiently compared to non-biodegradable plastics (Subramani et al., 2024).

However, the process of composting PLA requires specific conditions, such as high temperatures and controlled environments, which are not always accessible (European Bioplastics, 2024). In contrast to the PLA, PLA+ is widely used as an enhanced version for its biodegradability and with a better thermal stability and improved tensile strength, making it more suitable for a more complex application with its better flexibility (Anaç, Koçar & Altuok, 2024; Goryl et al., 2024; Hong, Choi & Han, 2009).

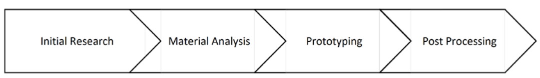
PLA is an eco-friendly variant and designed to be biodegradable, but it has less tensile strength as compared to the PLA+. In contrast, PLA+ focuses rather on the performance while PLA emphasises on the environmentally sustainable appeal (Pratama & Hasdiansah, 2021).

This research proposes a comprehensive framework for optimizing biodegradable materials in 3D printed fashion.

By addressing existing challenges and exploring innovative solutions, it aims to contribute to a more sustainable and creative future for the fashion industry. Sustainability is approached through responsible material selection and circular design strategies, with a particular focus on PLA+ as the primary biodegradable material due to its balance of printability, performance, and alignment with environmentally conscious practices, despite its inherent limitations. To address the issues on brittleness and thermal instability, this study explored innovative modifications and post-processing techniques aimed at enhancing the performance of PLA+ for fashion embellishments.

Method

A mixed-methods approach is used in this study, combining material experimentation, design prototyping, and qualitative interview with purposive sampling to explore the potential of biodegradable filaments for 3D-printed fashion garments. Illustrated in Figure 2, the methodology is structured into several interrelated stages to ensure a comprehensive understanding of material performance, design possibilities, and the practical application of biodegradable materials in fashion. It began with the initial research that involved reviewing literatures and interviews, then material analysis where three materials were examined and compared in terms of its properties and suitability for fashion embellishment creations. A standardized production workflow was followed for all samples, including design modelling, slicing, printing, and post-processing. Each material (Polyterra PLA, PLA+, bio resin) was printed in three repeated samples of equal size to ensure comparability. The results were then carried to post-processing stage that involved surface refinement, colouring, and finishing to enhance the visual appeal.



» **Figure 2:** *Research Framework*

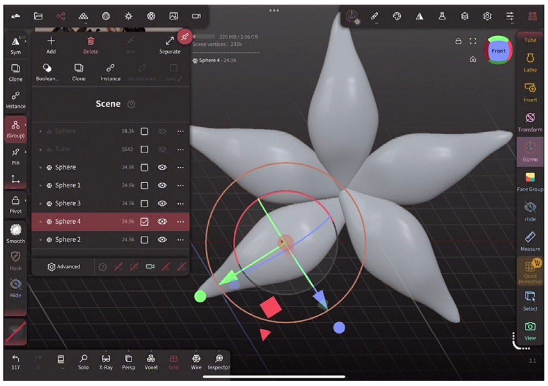
The data collection process in the interviews involves purposive sampling to ensure five interviewees possessed relevant expertise aligned with the study's objectives. They were selected based on their professional experience, technical knowledge, and familiarity with processes related to 3D printing, material development, sustainable practices, and high-fashion garment construction. Two fashion designers with extensive experience in eveningwear and advanced draping techniques were included to provide insights into aesthetic expectations, garment integration, and practical considerations in wearable design. To address the technical aspects of additive manufacturing, the sample incorporated 3D printing practitioners and engineering specialists with several years of hands-on experience working with different filament types, printer settings, and production workflows. Additionally, a sustainability expert from plastic recycling organizations and the waste management industry with a background in biodegradable plastic manufacturing contributed knowledge on material properties, environmental implications, and end-of-life considerations. These professionals provide broad perspectives from both fashion and engineering that guide the research process.

In addition to expert input, a survey was conducted with 56 respondents aged 25–40 who expressed interest in fashion, providing user-oriented perspectives on design appeal and sustainability values. This combined qualitative sampling approach ensured a comprehensive understanding of both technical and experiential factors relevant to developing biodegradable 3D printed fashion embellishments.

The obtained qualitative data is applied during the prototyping and experimentation phases. This includes prototyping 3D model designs, material experimentation, and design exploration. Desktop sculpting software Nomad Sculpt was used for developing the 3D designs. It was chosen as it is a lightweight application that can be done directly on mobile/tablet for faster prototyping and experimentation. The app offers a wide variety of functions and usage that allows a detailed rendering or 3D model. The good UI/UX allows user to easily sculpt and modify shapes into an intricate design. The features support rapid prototyping while offering a high-quality printing resolution. The application offers various textures, colors, background lighting to allow user in visualizing the final product or mock up with high similarity as the real size product design. Fashion embellishment prototypes were created in this study using PLA+ that can be applied for the creation of demi couture womenswear.

The design process began with initial sketching, followed by building the digital model in Nomad Sculpt using a basic sphere or cube as the starting form, illustrated in Figure 3. This base shape was then sculpted using various tools such as crease, clay, smooth, and drag brushes to define the structure, add depth, and refine surface details. Additional features, including creases, textures, and dimensional accents, were incorporated to enhance the visual complexity of the embellishment.

Throughout the process, the model's thickness was adjusted to maintain a 3D-printable minimum of 1.2–1.5 mm to ensure both durability and printability. Once the shape was finalized, smoothing and mesh retopology were applied to simplify the polygon count while maintaining the surface detail, resulting in a cleaner, a more detailed, and stronger print quality. The completed design was then exported as an STL file and prepared for fabrication through slicing software before the final 3D printing stage.



» **Figure 3:** *Sketching in Nomad Sculpt*

To strengthen the methodological rigor of the study, several step-by-step experimental procedures and basic material tests were incorporated. Each sample was produced using controlled settings, with melting temperatures ranging from 160–200°C and heating durations between 10–30 minutes, depending on the trial.

Tools such as silicone moulds, shredders, and digital thermometers were used to ensure consistency across samples, and all test pieces were created in similar sizes to allow fair comparison. After fabrication, a series of simple technical tests were conducted to evaluate the material performance. A flexibility test was performed by manually bending the samples to a 90° angle, where slight surface cracking indicated limited flexibility and low tolerance for bending stress. A drop test was also carried out to observe durability under impact. Surface smoothness was assessed visually on both the top and bottom sides of the samples, documenting irregularities such as bubbling, unevenness, or textural variations.

Colour consistency was examined after painting to identify how evenly pigments adhered across different material bases. Finally, heat exposure tests were conducted by placing samples under elevated temperature to observe deformation, brittleness, or texture changes. These basic yet systematic tests provided practical insights into the material behaviour and informed the selection of the most suitable biodegradable base for fashion embellishments.

Discussion

Biodegradable material is environmentally friendlier compared to conventional plastics making it a sustainable option. It offers less carbon emissions, lower levels of volatile organic compounds, and reduces air pollution during the printing process. Since it is made from renewable resources that can be composted, it decreases the carbon footprint, and the plastic waste issues as well. However, due to the limited infrastructure and government intervention that has been ongoing in Indonesia, experts mentioned that the end-of-life for biodegradable materials commonly ends up in sanitary landfills. It is a controlled landfill coated with plastic or geomembrane to prevent environmental pollution from the landfill. In fact, currently there is no industrial composting site available in Indonesia that requires high microbial activity, sufficient water content (at least 60%), sufficient air content, and adequate temperature, and high constant heat up to 60-degree Celsius. Consequently, most of the waste is handled by waste management services and some companies that produce biodegradable plastic. The waste is organised and processed, and if recyclable it is recycled; if not, then it is given to black soldier maggot to compost it, and if composting is not suitable, it is sent to the landfill.

There is another type of biodegradable plastic that is fully biodegradable, for instance PHA. However, due to its limited availability, it is very costly and requires specific printer and settings for it to be printed. For now, it is unavailable in Indonesia since it requires more infrastructure to have the specific machine that can print the PHA and the access to import the PHA filament.

Recycling could be another alternative aside from composting, but it is not recommended by some sustainable and 3D printing experts. The main challenge is that recycling the 3D printed waste decreases the quality in one or two cycles and not all plastic can be recycled. For instance, biodegradable plastic is meant to be compost not recycled. Furthermore, since it would lose its quality, experts and previous research noted that biodegradable plastic or plastic needs to be combined with virgin plastic.

There was already an attempt in Indonesia to use plastic bottle waste recycled as a filament however, there are still many issues encountered on the material consistency of various plastic bottles and still need more development. One alternative can be done is by assembling a machine to recycle used filament but there is still a shortage of spare parts and is still hard to find them especially in Indonesia. Due to the limited availability and inaccessibility of the spare parts, having to privately get it from abroad, most Indonesian 3D printing companies do not do and sell recycled filaments yet.

PLA may act as a good bio-based plastic, some of the most common are Polyterra and Esun. Based on the interview with experts, PLA is good for indoor use that are not directly exposed to sunlight with a quite food strength up to 100mph and it can withstand pressure. Even though it is not water resistant, it is still fine to be worn on body with sweat, only if it is regularly wiped for any water or liquid to prevent damage on the shape. Originally, PLA is not 100% pure plastic, it is a mixture of corn or wood fibre, making it not too strong as it absorbs moisture in humid temperatures. 28 – 30 to 33- 35 degrees Celsius is a good temperature for PLA.

It is fine to be worn in the daylight if it is not exposed for long hours and the heat does not reach to 60 degrees Celsius before PLA deflates or bends. Therefore, for long-term use, experts recommend covering the 3D printed PLA with resin for a more durable and water and heat resistant. Another alternative is to create a higher infill in the design model since thinner surface may cause the PLA to break easily; the infill needs to be around 80 – 100% to offer more durability.

Prototype making

To ensure the printed embellishments achieved the required durability, strength, and usability, the 3D printer was configured with optimized settings tailored for wearable applications. The table 1 below summarizes the key specifications and printing parameters used in this study for producing the prototypes.

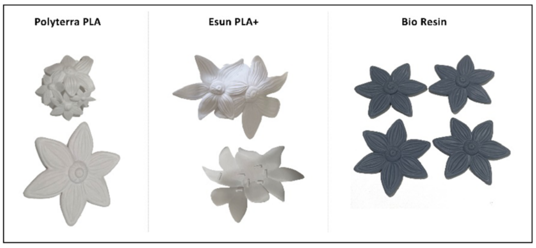
Table 1
Printer Setting

Model	Creality Ender 3 V2 Neo
Nozzle Size	0.4mm standard nozzle
Layer Height	0.12 – 0.20mm
Build Chamber Dimensions	220 x 220 x 250mm
Nozzle Temperature	200 – 210°C
Bed Temperature	55 – 60°C
Print Speed	50 – 60mm/s
Infill Percentage	100% for strength and support
Retraction	5mm / 45mm/s to reduce stringing

A corset prototype was developed in this study by assembling multiple 3D printed flower embellishments. The 3D modelling design was created imitating daffodil's flower structure and arranged onto the scanned 3D mannequin replicating the real-size body. The model was printed in different sizes, density and rotated to fit the body. By printing the flower singularly, the embellishment can potentially be applied for many arrangements or garments, for instance as accessories, tops, or as decorations. Also, it allows future alterations to fit on the different body proportions and sizing. Tiny loops were printed at the back of each flower to serve as attachment points for easy application on to garments. The current available 3D printer chamber has an average of 35cm x 35cm x 35cm in size, as a result, for large volumes printing, designs need to be divided and later assembled after printing for a larger scale. Lace, rope, or a chainmail can be used to assemble the small pieces for a larger scale application.

Prior deciding on the PLA+ as the primary material, the initial flower embellishment prototypes were produced using three different bases: bio resin, Polyterra PLA, and Esun PLA+ on an FDM printer. As shown in Figure 4, bio resin produced the most defined and detailed shapes, consistent with resin-based additive manufacturing research; however, its brittleness and higher cost made it less suitable for wearable embellishments. Although it easy to print using PLA, it showed visible cracking in the flexibility test and limited impact resistance in the drop test. This is aligned with prior literature describing standard PLA's low elongation and rigidity (Subramani et al., 2024; Xiao & Kan, 2022), confirming its unsuitability for embellishments that undergo even minor bending or handling.

In contrast, PLA+ demonstrated smoother surface finishes and greater resilience during testing, reflecting findings that modified PLA formulations offer improved toughness and interlayer adhesion (Li & Lee, 2022). Both PLA and PLA+ were printed using white filament to allow easier colouring during the post processing stage and to better see the shaping quality and appropriateness of the chosen material for an intricate shape. While bio resin was printed in grey instead of clear filament to allow easier external colouring. It would be harder to achieve the desired colour if clear filament was used.



» **Figure 4:** *Initial prototype making*

Post Processing

For the post processing, nail buffer and sandpaper were used for preparation before the colouring as well as perfecting the printed samples for a shinier and more polished finish. By doing so it helped in smoothing visible surface imperfections as well as impacting the overall finish quality (Alzyod, Takacs & Ficzere, 2024; Sawant, Shinde & Raykar, 2023). The final prototypes were made using PLA+ and best coloured using Tamiya Acrylic with additional topcoat using Acrylo water based.

It gave a smoother finish and enough shine for the colour silver. Prior this, trials were conducted using different colourants and colourants combination using Tamiya Acrylic, Tamiya Enamel, Acrylo, Mr. Hobby water based, and Mr. Hobby lacquer. These paints were hand painted, and air brushed during the trials. Table 2 summarises the comparative evaluation on different colourants used for PLA and Bio Resin.

Table 2

Comparative Evaluation on Different Colourants

Colourant	PLA, PLA+	Bio Resin
Tamiya Acrylic	Silver very glossy and shiny, lightest silver than the other paints	Shinier and glossier than using enamel paint
Tamiya Enamel	Very opaque finish, high shine, good consistency	Shinier finish than PLA base; has a lighter shade
Tamiya Acrylic + Acrylo water based	Has slightly more shine, smoother finish, lighter silver	
Mr. Hobby: water based	Not adhere well, paint to is watery; sheer gloss	Like Tamiya Acrylic but not that 'wet'; lighter shine
Mr. Color: lacquer	Very dull in colour, no shine	Very dull but since it is smoother, it has more shine compared to PLA base
Mr. Color: lacquer + Acrylo silver		More shine

To evaluate the functional performance of the 3D-printed fashion embellishment prototypes, several basic technical tests were conducted to assess flexibility, durability, surface quality, colour stability, and heat resistance. Prior studies noted that standard PLA tends to be brittle with low elongation (Subramani et al., 2024; Xiao & Kan, 2022), and this was confirmed through the technical tests conducted in this research. The flexibility test, which involved manually bending the embellishments to a 90° angle, resulted in fine surface cracks, demonstrating limited flexibility and reinforcing existing findings about PLA's inherent rigidity. Durability assessments further supported this, as the prototypes remained intact when dropped from heights up to 1.5 meters but developed cracks and slight deformation when dropped from 2 meters, indicating moderate impact resistance. These behaviours are consistent with previous research describing PLA's mechanical limitations and fragility under stress (Li & Lee, 2022).

Visual inspection of surface quality revealed a smooth and even top surface, while the underside exhibited a more textured, uneven finish, which is acceptable for embellishments since this area is not visible when attached to garments.

Previous studies have noted that heat and humidity exposure could degrade the results (Manoj & Panda, 2022; Goetjes, Zarges & Heim, 2024; Nugraha et al., 2023; Quader et al., 2024), this is in line with the colour consistency tests showing that prolonged exposure to heat caused noticeable yellowing, with higher temperatures intensifying the discoloration.

Heat-resistance testing further confirmed deformation above 160°C, reflecting the thermal sensitivity typical of PLA-based materials. These findings offer valuable insights into the prototypes' advantages and shortcomings, facilitating the assessment of their appropriateness for fashion embellishment applications where aesthetic appeal takes highest priority over high mechanical flexibility. Results from the mechanical and visual tests showed that PLA+ offered the best balance of flexibility, surface quality, and durability compared to Polyterra PLA and bio resin. While standard PLA was too rigid and bio resin too brittle, PLA+ withstood impact better and produced smoother printed surfaces, making it the most suitable material for the fashion embellishment.

To support the experimental findings, a questionnaire survey was conducted to assess public perceptions of 3D printing in fashion, their awareness and efficiency belief. The statistical results presented in Table 3 provide insight into how these technologies are perceived beyond the experimental context.

Table 3

Questionnaire results

Heard-before	Not sure	Yes, but only high fashion	Yes, reduces waste/ time	Row total
No	1	5	26	32
Yes	0	3	21	24
Column total	1	8	47	56

A chi-square test showed no significant association between prior awareness of 3D printing in fashion and respondents' beliefs that 3D printing improves fashion production efficiency, $\chi^2(2)=0.91$, $p=0.64$, Cramer's $V=0.13$. The χ^2 and p is used to address the question whether there is evidence of a relationship or not, while Cramer's V used to measure how strong the relationship is. The results show that the respondents largely believed 3D printing improves efficiency, with 83.9% selecting 'Yes, by reducing waste and production time,' 14.3% selecting 'Yes, but only for high fashion or experimental designs,' and 1.8% reporting uncertainty. This suggests that perceived efficiency benefits of 3D printing are broadly accepted within our respondents and do not differ meaningfully between respondents who had prior awareness and those who did not. In the context of this study, these findings reinforce the potential for biodegradable 3D-printed embellishments to be accepted as part of future fashion production, provided that material limitations and practical performance considerations are addressed. Furthermore, it highlights the value of exploring sustainable 3D-printing practices in relation to perceived benefits such as waste reduction.

Conclusion

By addressing material challenges and limitations, this study explored biodegradable materials for the creation of 3D printed fashion embellishments through a design-led and exploratory experimental approach. Evaluation was conducted through visual inspection and comparative qualitative analysis, focusing on surface smoothness, colour consistency, and overall aesthetic finish of the printed samples. While this approach is appropriate for early-stage material and design exploration, the absence of standardized instrumental measurements is acknowledged as a limitation. Future studies are therefore recommended to incorporate quantitative testing methods to further validate and extend the findings.

Table 4 summarizes the comparative evaluation of biodegradable options – Polyterra PLA, Esun PLA+, and bio resin – highlighting key characteristics, performance, and its suitability for garment embellishments. All three materials are suitable for making 3D printed embellishments however, their optimal use depends on the application requirements. While bio resin offers the highest level of detail for intricate and complex applications, its brittleness and cost make it less suitable for wearable components.

In contrast, standard PLA such as Polyterra PLA, with its lower elongation and rigidity, is better suited for decorative pieces or detachable elements that experience minimal physical stress. Modified PLA such as Esun PLA+ provides higher elongation and greater flexibility, making it more suitable for structural embellishments and wearable components that require both movement and durability.

Polyterra PLA is a biomass filled material blended with wood flour or corn starch, resulting in a matte surface texture, low odour, and a relatively low melting point. While it is easy to print and environmentally conscious, its mechanical performance is moderate, with noticeable brittleness under stress. This makes Polyterra PLA suitable for decorative or detachable eco conscious embellishments that experience low physical stress. On the other hand, Esun PLA+ is a modified PLA with strength additives like corn flour. From the experiment results, it shows that Esun PLA+ has a better flexibility that supports structural embellishments aligned with previous research. From a cost perspective, Polyterra PLA is the most affordable option, followed by PLA+, while bio resin remains the most expensive.

In this study, PLA+ emerged as the most appropriate material due to its balanced combination of strength, flexibility, and printability, producing prototypes that held their form while demonstrating better resilience and smoother surface finishes compared to Polyterra PLA and bio resin.

These combined findings particularly the improved surface quality, stronger impact resistance, and moderate flexibility offer clear empirical justification for selecting PLA+ as the primary material for the final embellishment prototype. This supports informed material selection and strengthens the integration of sustainable, functional 3D-printing practices within fashion design and production.

Across all materials, surface roughness could be minimized through sanding; however, the use of colorants, while improving aesthetics may negatively affect tensile strength. For a smoother surface finish can be achieved through airbrush painting, with the application of primer further enhancing gloss and surface uniformity.

Figure 5 depicts the making process of the 3D printed fashion embellishment while Figure 6 shows the various sizes and colour finishes of the 3D printed fashion embellishments that were created in this study. It began from the inspiration image that was taken as reference for visual and structural for the design model. Then digital model was created and sculpted using Nomad Sculpt with consideration to the scales, sizes, and arrangement for its application on the garment. It facilitated in conceptualising, refining the embellishment, and playing with scales and arrangement prior to the printing.

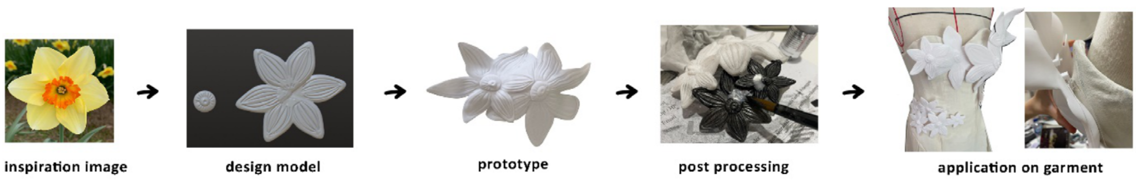
Once the design was achieved, it was 3D printed using PLA+ filament to create physical prototype. In the post-processing phase, the prototype was cleaned, sanded, and painted. Sanding is needed prior colouring to smoothen any rough edge and imperfections because of the printing. It was then hand painted using Tamiya Acrylic and top painted with same colour Acrylo water-based paint. The embellishments then were attached on to garment by stitching the loops to the fabric using sewing thread.

While the experimental results demonstrate aesthetic promise and sustainable design potential, further studies are needed to enhance the quality and functional performance of 3D printed embellishments. It would benefit from testing on a wider range of colouring techniques to better explore on the colorants, combinations, the application of top or base coat and colouring techniques to expand design possibilities.

Practical considerations on the aftercare in terms of cleaning and washing and embellishment attachment methods to garment must also be assessed. In addition, further study on material resistance to environmental factors namely heat, UV, and humidity is highly recommended to ensure long term wearability. Overall, this study contributes to the advancement of 3D printing by optimising biodegradable materials for a more sustainable and creative design potential for the fashion industry.

Table 4
Comparative Evaluation on Biodegradable Materials

<table>
<tr><th></th><th>Polyterra PLA</th><th>Esun PLA+</th><th>Bio Resin</th><th>Source</th></tr>
<tr><td>Material Composition</td><td>Biomass filled; blended with wood flour / corn starch</td><td>Modified PLA with strength additives like corn flour</td><td>Plant based: soybean oil, lactic acid, or castor oil</td><td>(Byjus, 2018; Khosravani & Reinicke, 2020; Conniff & Tewolde, 2022)</td></tr>
<tr><td rowspan="2">Key Characteristic</td><td>Matte texture, low odour, low melting point</td><td>Glossy finish, better layer adhesion, more flexible, stronger</td><td>Strong, high-detail finish, UV curable</td><td>(Cisneros-López et al., 2020)</td></tr>
<tr><td>Printing result just okay</td><td>Smoother finish</td><td>Shapes & lines are more defined</td><td>Based on experimentation</td></tr>
<tr><td>Durability</td><td>Moderate, somewhat brittle but improved; best for decorative – low stress embellishment</td><td>Better flexibility and strength for structural embellishments</td><td>For high detail embellishment, very intricate</td><td>Based on experimentation; (Li & Lee, 2022)</td></tr>
<tr><td>Resolution / Surface Quality</td><td>Achieve surface roughness 7-8 µm</td><td>Offers enhanced tensile strength with a better resolution</td><td>Can achieve as fine as 25-30 µm</td><td>(Lim et al., 2018; Mushtaq et al., 2024)</td></tr>
<tr><td>Heat / Water Resistance</td><td colspan="3">Environmental conditions like humidity and heat reduces the hardness and tensile strength with notable physical degradation and cracks</td><td>(Manoj & Panda, 2022; Goetjes, Zarges & Heim, 2024; Nugraha et al., 2023; Quader et al., 2024)</td></tr>
<tr><td rowspan="3">Post Processing</td><td colspan="3">Sanding is needed to improve surface roughness; colorants may enhance the visual appeal but may reduce tensile strength</td><td>(Alzyod, Takacs & Ficzere, 2024; Sawant, Shinde & Raykar, 2023; Son & Lee, 2020)</td></tr>
<tr><td>Best to colour using Tamiya Acrylic hand painted and top it off with same colour Acrylo water-based paint</td><td colspan="2">Hand painted for higher resolution of the lines; use Tamiya Enamel</td><td rowspan="2">Based on experimentation</td></tr>
<tr><td colspan="3">For smoother surface: air brush painting gives smoother finish; results are glossier, smoother, and shinier if primer is used</td></tr>
<tr><td>Price</td><td>Cheapest</td><td>Moderate</td><td>More expensive</td><td></td></tr>
<tr><td>Suitability for Garment Embellishment</td><td>Eco conscious embellishments; for detachable elements; with low physical stress</td><td>Good for structural and complex embellishments</td><td>Best for intricate and more complex application</td><td>Based on experimentation</td></tr>
</table>



» **Figure 5:** *The making process of the 3D printed fashion embellishment*

» **Figure 6:** *The final 3D printed fashion embellishments*

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