

An Analysis of Sustainability and Sustainable Material Options for 3D Printed Prototypes

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Abstract

When considering how temporary each iteration of a prototype is, its end-of-life phase should be evaluated just as thoroughly as the prototype itself. So, as more companies prioritize sustainability, can 3D printing be viewed as a practical technology for prototyping when considering the plastic waste it produces? Both 3D printer plastic waste and 3D printing's use in prototyping have already had their share of academic research done about them, but the gap where these topics overlap lacks content. After looking at alternative prototyping methods, 3D printers were in fact a very strong prototyping method because of their accuracy, material efficiency and ability to create unique one-of-a-kind forms. The material used for 3D printing was evaluated next, and while it was found that the most common material, PLA, was a big contributor to plastic waste, it had the ability to be recycled. Prototypes using 3D printing as their fabrication method likely are not concerned about accurate colour, material finish or strength, and if that was needed, it would be recommended to use the materials or fabrication method of the final product. What really matters on 3D printed prototypes is their dimensional accuracy and ability to create forms as intended. To test the viability of using recycled PLA instead of virgin, both materials were acquired, used to print the same test model, and evaluated on their outcome. Visually both prints had similar results on the official tests done, but the differences began to show when the prints were measured, looked at in detail and handled. The virgin PLA printed closer to the intended dimensions, with both prints being within a millimeter of the expected results, had cleaner text detailing and was more durable than the recycled PLA print. This study finds that 3D printing can definitely be considered a great prototyping method for companies looking to increase their sustainable practices, as long as they ensure recycled materials are used when possible and virgin materials used are properly disposed of.

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Introduction

A paradox is arising in 2024 as companies who stay up to date on the newest trends and technologies are the ones really investing in sustainable practices, but also the most likely to consider using plastic waste producing technology such as 3D printing. As more companies prioritize sustainability, can 3D printing be viewed as a practical technology for prototyping when considering the plastic waste it produces? This study will not focus on the use of 3D printing in a particular industry, but will centre around its use in prototyping as the iterative nature of prototypes leaves these plastic products destined for disposal after a very short life of use.

3D printing, also known as additive manufacturing as pieces are formed by adding layer on top of layer to create a final product, differs from traditional subtractive manufacturing's milling or carving process to take away material from a larger mass to achieve a final shape (Savini, 2015). There are many different processes classified under the term "3D printing", but this study will focus on Fused Deposition Modeling, or FDM, which is the most common process used in prototyping currently (Apaçoğlu-Turan et al., 2024). In the early 2000s 3D printers were almost exclusively used for prototyping in large companies (Savini, 2015), but as the technology has grown in popularity and accessibility to small businesses, students and even just hobbyists, the material waste associated with it has also increased dramatically. To explain the FDM process as simply as possible plastic filaments are fed into a heated nozzle that has the ability to move as it extrudes the material, carefully building a 3D shape layer by layer as the plastic solidifies, following a digital file that acts as a blueprint for the final product (Apaçoğlu-Turan et al., 2024). Other methods of plastic fabrication that are still classified as 3D printing include resin printing in the form of stereolithography (SLA) or digital light processing (DLP), which hardens each layer in resin with UV light and finds its application most commonly in jewelry and dental products, and selective laser sintering (SLS) where each layer is formed with a laser and material in the form of powder (Schwaar, 2024).

This study will first review literature that explores why 3D printing has grown so greatly as a prototyping method and its benefits compared to other fabrication methods, then alternative processes and materials that could be used in prototyping. Next, a comprehensive review of the literature identifies how relevant the available sources are to this specific topic, as well as how gaps in academic studies are being filled in by forums, blogs and the general internet. Focusing on two polylactic acid materials, tests were chosen to compare virgin material to recycled material, evaluating a potential solution to reducing plastic waste. Finally, the results of these tests were compared based on the factors tolerance, detail, overhangs, bridging, durability, and dimensional accuracy to determine if the recycled material could be a replacement for virgin material with its current characteristics. This study aims to be a resource for companies who are

interested in reducing their plastic waste, but still find value in 3D printing as a technology for creating their prototypes, as well as companies who may have resisted purchasing 3D printing equipment in the past and are still looking to learn more about the emerging technology and the least wasteful way to use it before they begin their investments.

Glossary

ABS - Acrylonitrile-Butadiene-Styrene. A common thermoplastic used in 3D printing made from petroleum. Known for having high heat resistance and durability properties at its affordable price point.

Additive Manufacturing - Another term for 3D printing. A 3D form is built up as material is deposited layer by layer by an automated machine.

CAD - Computer Aided/Assisted Design. Software used to assist a designer in their work. Common CAD software used in 3D modeling is used to create a digital version of the prototype, which can be tested or shared virtually before physical fabrication.

FDM - Fused Deposition Modeling, also sometimes referred to as Fused Filament Fabrication, or FFF. Most common 3D printing process used in prototyping currently. Material is extruded through a nozzle in layers to create complete 3D forms.

Infill - To save time and material, most 3D printed objects are not printed completely solid, but the structure also usually needs some kind of interior support. Infill settings determine what percentage of the interior will be filled and what shape the filling will take.

PLA - Polylactic Acid. The most popular thermoplastic used in 3D printing. Known for its low cost, low melting temperature and ease to work with.

Slicer - A software that connects and translates a 3D model to a printable, layer by layer form and provides instructions to the printer on how to complete the print.

Supports - Removable material added to a piece to support overhanging structures during printing. Additive manufacturing relies on always having a previous layer available to add the new one on.

TPS - Thermoplastic Potato Starch. A compostable bioplastic being tested for its use in 3D printing as an alternative to PLA.

Literature Review

Introduction

While much research has already been conducted on both the use of 3D printing technology as a prototyping method and on the environmental impacts of 3D printing materials, there is still a large gap of knowledge on how these two topics overlap and affect each other. With the first group of researchers optimistically arguing that 3D printing technologies are the future of the prototyping industry (Pavlov, 2021) and the second group focusing on the reality of microplastics that enter the environment as a result of disposed plastic products (Chiodoni et al., 2020) it is time that the evidence for both sides is compared. There is a final group that is also quickly growing a strong body of research related to these topics, and just might be the answer to finding a compromise for sustainable prototyping with 3D printing technology. This group is looking at the possibility of recycling and reusing common plastic materials used in 3D printing to give them more than a “single-use” life, and also, alternative material that could be used as a replacement for traditional plastic materials.

This literature review will first look at works that analyze the benefits of using 3D modeling and 3D printing in a company’s prototyping process, what makes it unique and why it has been predicted to become so popular in many industries for this application (Formlabs, 2022). Next, it will review the opposing side and what environmental issues have been found with the process, and specifically, the environmental concerns related to the common plastic materials used. After that, literature on other possible prototyping methods will be analyzed to compare and contrast prototyping options available to companies other than 3D printing. Finally, it will look into what research has been done on alternative, more sustainable filament materials that can be used with 3D printing technology.

Benefits of 3D Printing as a Prototyping Method

To start off, what are the benefits and advantages of using 3D printing as a prototyping method? If there are concerns surrounding the environmental impact of the technology, then what are the incentives to use it for such a temporary product? These questions are quickly answered by looking at literature covering a process called “rapid prototyping” and literature on how computer aided design, or CAD, modeling is being used to prototype products first virtually, and then easily come to life through the additive manufacturing process that works with the same, already made CAD files (Budinoff & Kramer, 2022). Overall, there are many reasons why companies have recently been investing more and more to get 3D printing into their product development processes.

Traditionally prototyping has been known to be the bottleneck of the product development process because of the associated high cost and time contribution needed to produce visually or dimensionally accurate designs. It is not uncommon

for a prototype that is intended to look or function as the final design will, to need the same traditional, expensive manufacturing processes as that final part (Formlabs, 2022). With all these complications involved in making an item not even seen by the public, it is clear why rapid prototyping methods are growing so quickly in popularity. In fact, the market size for the rapid prototyping industry is expected to grow from a value of \$2.76 billion USD in 2023, to \$14.78 billion in 2032 (Precedence Research, 2023). One way that 3D printing proves itself as a rapid method of making these prototypes is that the manufacturing, the actual layer by layer construction of the physical piece, can happen overnight and unattended (Formlabs 2022). The product construction can happen outside of working hours, or even in the background as the next version of the design is being created. In addition to the speed benefits of this method, using 3D printing to prototype also allows complex, freestanding shapes to be created quite easily (Nida et al., 2021). A 2021 study explored the unique ability to enclose other materials into a 3D print while a piece is being fabricated on a printer for seamless integration of multiple materials in one part. A few example use cases of this concept are reinforcing the product's strength with a layer of wire or mesh placed down between layers, encapsulating glass to act as a window in a frame, or adding magnets, near field communication chips or screw nuts seamlessly into a product to add functionality and push the prototype closer to the final product's design (Pavlov, 2021).

A fascinating, and impressively committed experiment of 3D printing's capabilities was done by GE Aerospace who, in 2018, started rethinking their whole new product development process to center it around additive manufacturing. The company transitioned from creating its fuel nozzle tip for its LEAP Jet engine with 20 individually casted, forged and welded pieces, to creating it in additive manufacturing in just one piece (Roscoe et al., 2023). The company realized this manufacturing method produced a piece that weighed 25% less, was 5 times more durable and 30% more cost-efficient than the original piece and decided to make the huge commitment to invest enough in their 3D printing operations to start using it for mass production (Kover, 2018). It is commonly known that time is money in any business, so 3D printing supporting rapid prototyping is a huge benefit of the technology (Cole, 2023).

Generally, a 3D print starts as a CAD file that has been produced using a 3D modelling software or through a 3D scan of a real world object (Roscoe et al., 2023), so even before the actual printing of the physical product begins, this manufacturing method has many benefits. One use that has been growing in popularity, especially as remote work becomes more common, is the ability to have digital files that can be shared, collaborated on and reviewed instantly with a whole team, no matter the distance between them (Cole, 2023). Adding onto that, the ability to simulate tests on a virtual prototype before committing to making a physical piece saves time, money and resources for a business. This technique was looked at in 2022 in the area of fresh fruit package design and the

study came up with some great virtual prototyping tests, including compress strength and airflow ventilation simulations (Ambaw et al., 2022). As computers become more powerful, the ability to access and perform these complex situations becomes more accessible to businesses of all sizes. Other interesting applications for prototyping with CAD models include virtual or augmented reality testing to visualize a product in use or on display in store and 3D renders, which are excellent tools to help team members, supervisors or customers visualize your product and be convinced on its design (Budinoff & Kramer, 2022).

Environmental Concerns

Although additive manufacturing produces less material waste than subtractive manufacturing, as the shape is not formed through the reduction of a larger piece of material (Mark Forged, 2022), prototyping is still a very iterative process with each finished product not intended to last long and is a source of waste in manufacturing. While there is much debate on the overall carbon footprint of 3D printing compared to traditional plastic molding methods, such as injection molding, this literature review will focus primarily on plastic waste. However, just to provide one example of this overall sustainability debate, while 3D printing is found to use more energy when actually producing each part, it is also found that 3D printing's shorter supply chain could offset this (Bezzina & Refalo, 2023).

The most common material used for 3D printing currently is polylactic acid, or PLA, with 47.2% of the global filament market (Vidakis et al., 2020). PLA gains its popularity because it has a relatively low cost, does not release fumes during printing, prints at a low temperature and can easily be sanded and painted for further development of the prototype (TWI, n.d.). PLA is technically labelled as a bioplastic, but a life cycle analysis conducted on the material is quick to point out that most of PLA's sustainability claims are dependent on the user's care to properly dispose of the material after use (Rezvani et al., 2021). PLA is recommended to be sent to special, very specific composting facilities if it is expected for the bioplastic to actually break down. A 2017 study testing PLA's ability to biodegrade at ambient temperatures found absolutely no change to the plastic after one year of being out in a seawater environment (TWI, n.d.). As any degradation that does happen to the material outside of a specialized facility becomes another source of nanoplastics releasing into the environment (Chiodoni et al., 2020).

Another common material used is Acrylonitrile-Butadiene-Styrene, or ABS, which holds 29.1% of the global filament market (Vidakis et al., 2020). ABS immediately presents itself as the less sustainable filament option as it is made from petroleum, as opposed to PLA's corn or sugarcane starch base (Prior, 2023). ABS is popular as it is very similar in price to PLA, but has a higher heat resistance and durability. The possibility of saving ABS from the landfill at its end of life has been explored in a study that tested low density polyethylene/ABS blends and

the possibility of improving structural, thermal, mechanical and gas barrier properties of the final material (Saxena & Maiti, 2021), but this still requires careful, specialized disposal of the material by the user to ensure it ends up in the right facility.

Alternative Prototyping Methods

If 3D printing is not an option for a company, there are still other ways to create a prototype. As mentioned earlier, subtractive manufacturing is an alternate process that creates a 3D shape and was a popular method before additive manufacturing entered the market. This technique involved CNC milling, cutting, drilling and/or carving away material to result in a finished prototype (Laszeray, 2019). Benefits of this method include smoother surface finishes, eliminating the “layer steps” visible on most additive manufactured parts before sanding or further finishing, wide variety of materials such as woods and metals as well as plastics, but not limited to meltable (often proprietary) thermoplastics as 3D printing is, and the close imitation of tolerances to injection molded parts, which is often used as a mass production process after the prototyping stage. This process so similarly reflects injection molding as a method called rapid injection molding falls under the subtractive manufacturing category as well. Injection molding is already a very quick process so what classifies this method as “rapid” is the aluminum mold being much faster to manufacture than a steel mold made for durability and reuse (Langnau, 2011). The drawbacks of this process include material waste and inability to create certain geometries, for example not being able to create a hollow shape with CNC milling (Savini, 2015).

If multiple of the same prototype is being made, casting is a potential alternative method to consider. Perhaps many different tests, or repetition of the same test need to be conducted on a group of prototypes and a mold made will need to be used more than once. This method provides far more consistency between each piece than could be produced through a 3D printing method, as a rubber mold is filled with resin to produce identical parts (Laszeray, 2019). However, this method is only justifiable for producing high quantities of prototypes with its high associated time costs.

Alternative Material Options

Perhaps the most obvious material option to turn to with the goal of increasing sustainability is the post-consumer, or recycled version of the already common PLA and ABS materials. The Canadian filament supplier Filaments.ca makes a recycled PLA product out of waste from the manufacturing of their non-recycled filament options that is available for consumers to buy for the same price as their other standard PLA (Filaments.ca, 2024). In order to maintain quality in recycled PLA products, only 60-80% of the material can actually be the recycled material, with the remaining still composed of virgin plastics (Gil Muñoz et al., 2020). This

material is made from different colours each batch, so not only is it not possible to order a specific colour from this recycling method, but filaments ordered at different times will also have variety in appearance (Filaments.ca, 2024).

Alternatively, Filaments.ca also offers a program that accepts and recycles consumer 3D printer waste. Materials accepted include PLA, PETG (Polyethylene terephthalate glycol) and ABS, but these materials must be sorted from each other and not contaminated with any other material to be accepted. They offer this service free of charge, but note that “The process of recycling plastic from 3D printing scraps is very labor intensive, time consuming and is significantly more costly than processing virgin material” (Filaments.ca, 2024) and the consumer does not get a specific benefit for contributing material, other than responsible disposal of their waste. This recycling program stands out as it has a specific workflow for handling old prototypes. Filaments.ca accepts prototypes of any size that will be discreetly broken down with proof of destruction. This incentivises companies to recycle their old prototypes instead of sending them to landfill as it adds the extra security layer of ensuring internal designs are not discovered by the public or the company’s competition (Filaments.ca, 2024).

If you stray away from traditional filament materials there are more options, many of which are still in the development stage, but could soon become a viable material alternative. One example tested in a 2021 study is sugarcane bagasse. This biodegradable material was used for 3D printed package casing for low-moisture foods, as its absorptive properties result in swelling and loss of strength when exposed to moisture over several days. Likely prototypes at the 3D printing stage will not need to actually contain products, and would align with the study’s findings that this material would be best used for one time use products, such as take-out cutlery (Nida et al., 2021). Another interesting material combined PLA with TPS, or thermoplastic potato starch to make a bioplastic with excellent printing capabilities, but again, there is an issue with moisture absorption (Haryńska, 2021).

Finally, using other recycled plastics to create filament is a possibility being explored. A pre-consumer recycled polypropylene filament showed similar tensile strength values to a typical 3D printer filament, but needed a custom retrofitted printer and printing bed due to its lack of adhesion (Stoof & Pickering, 2018). Interestingly, all seven main types of recyclable plastic (polypropylene, polyvinyl chloride, high- and low-density polyethylene, polystyrene, polyethylene terephthalate, and others such as ABS and polycarbonate) technically have been considered for their re-use in filament, but the main reason development has not gone beyond just testing the possibility is the loss of strength and stability properties after several recycling cycles, and more prominently the lack of economic incentives for the use of recycled materials (Mikula et al., 2021).

Conclusions

The literature reviewed collectively points to 3D printing as a strong prototyping method with many benefits as far as time efficiency, low cost and the convenience of printing off a CAD file. However, the need to reduce plastic waste cannot be overlooked and supposedly compostable PLA is not going to biodegrade unless properly taken in by a specialized facility (TWI, n.d.). 3D printing does have excellent material utilization in comparison to a subtractive manufacturing method, even when accounting for failed prints and removable supports (Bezzina, 2023) and does not require a whole mold to be made for each prototype iteration as injection molding or casting would. Overall from a company's point of view the ease of making a component without huge investment in tooling makes 3D printing an obviously popular technology for disposable prototypes and proves the technology will not be leaving the space anytime soon (Mikula et al., 2021).

So, instead of looking for an alternative process of creating prototypes, alternative materials and disposal methods for current 3D printing technology is likely the best solution. Progress is already being made in materials that are not as durable or long lasting as traditional plastics, but likely do not require to be for the use of temporary internal prototypes, such as the easily biodegradable option sugarcane bagasse or the recycled plastic options. After all, if the material is properly disposed of by a composting facility for PLA, or a recycling facility for PLA or ABS, the plastic does not cause as much harm to the environment as ending in the landfill (Chiodoni et al., 2020). If a company is looking to do a lot of 3D printed prototyping, then it is likely in their best interest to become educated on proper disposal of their old prototypes, and can even get some benefits of this proper disposal, like the destruction of sensitive prototypes service offered by Filaments.ca.

Currently recycling plastics into filament is an energy intensive process with little to no economic incentive for companies to use over using virgin material for their work, unless they are using it as a method to hit corporate sustainability goals. If more research and development is put into making the recycling process of common 3D printed waste cheaper and easier, with more consistent colour and lower ratios of virgin material used in each batch, then this would likely be the best solution for sustainable additive manufacturing prototyping in the future.

Comprehensive Review

Literature Sources

The database websites used to find academic literature for this literature review were Google Scholar and the Toronto Metropolitan University (TMU) Library. These databases came back with many results for topics related to parts of this

thesis, but lack of literature on the overlap between 3D printed prototyping and sustainability are clear.

Searching the TMU Library first for peer reviewed and scholarly articles with the keyword “3D printing” comes back with an outstanding 66,047 results and only narrows down to 48,890 if you look for literature only published in the last 5 years, from 2019 to 2024. To narrow the search down much further, more keywords were added to the search next. Searching the database for articles containing both the keywords “3D printing” and “prototyping” from the past 5 years cuts down results to 3,414 options. Finally, adding all three keywords “3D printing”, “prototyping” and “sustainability” and looking for work from the past 5 years, a manageable 142 results come up. If just the keyword “prototyping” is used to search, the database comes up with 43,693 results, and with just the keyword “sustainability” 1,339,834 articles appear.

If the same keywords are run through Google Scholar, with its much larger database, the results for each topic are nothing but overwhelming. A search for “3D printing” returned about 2,780,000 results, “prototyping”, the lowest numbers returned from each database, returned about 1,120,000 results and “sustainability” returned about 4,770,000 results. When the same techniques of using all three keywords and only returning literature from 2019 to present day are applied, about 16,800 results were returned, greatly cut down from the previous millions of results.

Topic Relevance

Within the results of the used databases, many results were not particularly relevant for use in this study, covering topics such as 3D printing with concrete in construction or metal in the aircraft industry, or biomedical application of 3D printing. If the search for sources was to be done again, another filter with the keyword “plastic” would be added to narrow down results even further. Focusing on the academic articles that contributed to this study, many can be divided into broader topics as a wide variety of articles from different industries had to come together to complete this literature review to its fullest extent. Table 1 illustrates the general topics of the literature sourced for this review. Each source is put into one or more broad categories based on the topics it covers.

Topic	Relevant Literature
CAD & Virtual Prototyping	Fresh fruit packaging design verification through virtual prototyping technique, CAD as a Virtual Prototyping Method: Uses and Timing of Computer-Aided Design Artifacts in Hardware Design, A short history of 3D printing, a technological revolution just started
3D Printed Prototyping	3-D Modelling and prototyping of complex-shaped heterogeneous parts, Transitioning additive manufacturing from rapid prototyping to high-volume production: A case study of complex final products, A short history of 3D printing, a technological revolution just started
3D Printing	Evaluation of the Circularity of Recycled PLA Filaments for 3D Printers, Transitioning additive manufacturing from rapid prototyping to high-volume production: A case study of complex final products, 3D printed food package casings from sugarcane bagasse: a waste valorization study, A short history of 3D printing, a technological revolution just started
FDM Printing	Numerical Modeling and Analysis of Transient and Three-Dimensional Heat Transfer in 3D Printing via Fused-Deposition Modeling (FDM), Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene
FFF Printing	Fused Filament Fabrication and Injection Moulding of Plastic Packaging: An Environmental and Financial Comparative Assessment, PLA–Potato Thermoplastic Starch Filament as a Sustainable Alternative to the Conventional PLA Filament: Processing, Characterization, and FFF 3D Printing
Plastics & Sustainability	Fused Filament Fabrication and Injection Moulding of Plastic Packaging: An Environmental and Financial Comparative Assessment, 3D printer waste, a new source of nanoplastic pollutants, 3D printing filament as a second life of waste plastics—a review
Traditional Plastics	Evaluation of the Circularity of Recycled PLA Filaments for 3D Printers, The Life Cycle Assessment for Polylactic Acid (PLA) to Make It a Low-Carbon Material, Utilization of ABS from plastic waste through single-step reactive extrusion of LDPE/ABS blends of improved properties, Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene, Sustainable Additive Manufacturing: Mechanical Response of Acrylonitrile-Butadiene-Styrene over Multiple Recycling Processes
Alternative Plastics	3D printed food package casings from sugarcane bagasse: a waste valorization study, PLA–Potato Thermoplastic Starch Filament as a Sustainable Alternative to the Conventional PLA Filament: Processing, Characterization, and FFF 3D Printing

Table 1: Literature Topics Used For This Review

Since 3D printing is growing in popularity at the consumer level, some of the most relevant sources covering all keywords of this research were found in websites, blogs and forums. It is understood that these sources are not peer-reviewed and likely have their own biases or knowledge gaps, however sources used for this article were critically examined for their credibility before their addition to this research. Internet sources came from 3D printer manufacturers speaking to the capabilities of their different products, companies currently using 3D printing as a prototyping method and reporting how successful they have been and what challenges they have had to overcome and hobbyists having genuine questions on the quality of different materials or what to do with their own 3D printed waste. While much of the current academic literature covers new, niche or non-traditional materials and methods, future academic literature is needed in this area that primarily internet sources currently cover, addressing additive manufacturing's use in different industries and in a variety of company sizes, with materials and equipment available to the average business creating prototypes.

Research Methodology

Selected Materials

To investigate the possibility of companies switching to recycled filament materials for their 3D printed prototypes, these next tests will compare and contrast different aspects and characteristics of recycled PLA and virgin PLA materials. Both filaments tested are ordered from Filaments.ca, with the recycled PLA coming from their filament recycling program mentioned earlier. Both the Recycled PLA and the EconoFil™ Standard PLA Filament were ordered as a 1kg spool of 1.75mm thickness. These filaments are also both newly ordered at the same time for these tests, as opposed to using filament that was already on hand or had been owned for a while. Purchasing new filament for these tests was done to ensure results were not skewed due to one material having a higher moisture content or more wear and tear from previous use and handling. Both materials have the same 215°C recommended printing temperature, 55°C-60°C recommended hot bed temperature and price when purchased (Filaments.ca, 2024).

Selected CAD Model

To test many characteristics of each filament in one print, a free downloadable model was found that includes 6 different tests in one print (Figure 1). The "Micro All In One (AIO) 3D Printer Test" was created by Marián Trpkoš in 2018 and has been downloaded from the popular CAD model sharing website Thingiverse.com over 16 000 times. This model is an updated version of an even more popular model made by the same designer. This 5cm x 5cm x 5.6cm "micro size" version was chosen for this research as it included all the same tests, just in a more

compact layout which would take less time to print each piece. The tests included in this model and their purposes are shown below (Table 2).

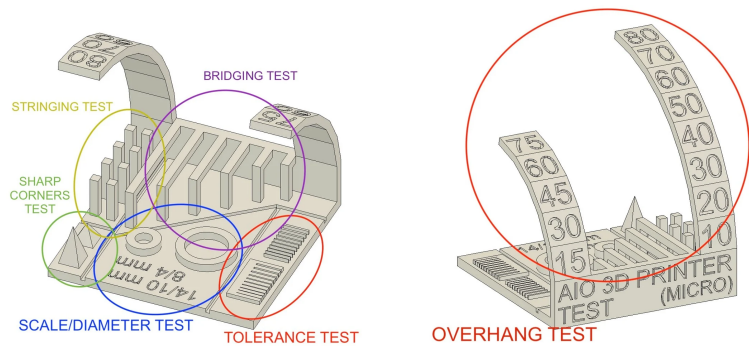


Figure 1: Labeled test areas on the 3D calibration model
<https://www.thingiverse.com/thing:2975429>

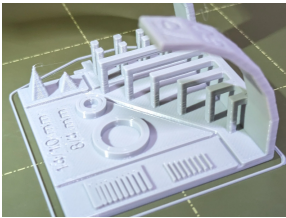
Users on Thingiverse.com are able to post pictures of how their model printed to share what worked for them, what did not, what settings they used, etc. With over 250 prints shared, these images give us an excellent idea of successful and unsuccessful prints of each test and what to look for when the test is conducted to compare the recycled and virgin filaments for this research (Table 3).

While this test is also useful for troubleshooting printer settings such as an uncalibrated nozzle, over extrusion or issues with belt tension, both prints will be done with the same printer settings, so any printer related issues found will appear on both test prints and will not affect the results when comparing the filaments. In the case that a printer setting needs to be tweaked in between prints in order to continue printing, both prints will be restarted so that the filaments are compared as accurately as possible.

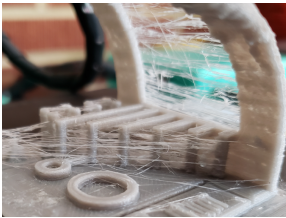
This CAD model emphasizes dimensional accuracy in its tests, making it a great choice to use for the testing of different materials for their use in prototyping. If a company is choosing to create a prototype using PLA and additive manufacturing, instead of the final product's materials and manufacturing process, colour, strength and finish are likely less important to accurately reproduce.

Test Name	Test Purpose
Stringing Test	When the print head moves from one section to another, over an open area, or gap, filament drips from the nozzle causing a stringy connection between pieces (Jennings, 2022). This effect happens if the nozzle is too hot, or the filament is melting below the recommended temperature, or if there is excessive moisture present in the filament (Obudho, 2024).
Sharp Corners Test	A well calibrated 3D printer should have the ability to print sharp corners and not struggle to show fine detail. This test often exposes cheaper filaments from more expensive options as the chemical composition has an impact on the filament's flow and set (Jennings, 2022).
Scale/Diameter Test	This test is generally used to help visualize a printer's abilities with dimensional accuracy. Ideally the circle is symmetrical and round. This test applies more to printer calibration than filament quality.
Tolerance Test	Another test for dimensional accuracy in a print, this one is specifically important when making pieces that fit closely together. When referring to "tolerance" in filament, the term refers to the filament's diameter. In this case filament tolerance can be measured with digital callipers and, based on the purchased filament, should register between 1.73 mm-1.77 mm as the 1.75 mm product claims to have a ± 0.02 mm tolerance (Galiki et al., 2023). When the print is finished, the overall print tolerance and dimensional accuracy can be measured with calipers as well.
Bridging Test	Unsuccessful bridging will have filament sagging between two supports on either side when printing over a gap. If filament is melting at a lower temperature than the recommended setting, this can cause unsuccessful bridge tests (Jennings, 2022).
Overhang Test	This test demonstrates the printer and filament's ability to print unsupported offset angles branching out from the base of the print. If the filament material is not cooling quickly enough to harden in place attached to the previous layer, this can cause issues with overhangs. Low quality filaments with a high level of impurities or filaments that have a high moisture content will also struggle to produce clean results in this test (AnyCubic, 2023).

Table 2: Test Names, Purposes and Examples



Successful



Unsuccessful

Stringing Test
(Thorton, 2024 & Fisher, 2020)

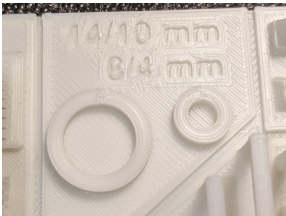


Successful



Unsuccessful

Sharp Corners Test
(Holmes, 2013)



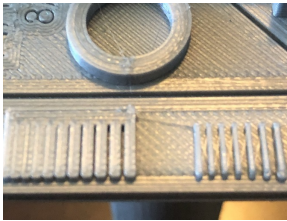
Successful



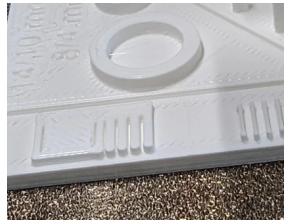
Unsuccessful

Scale/Diameter Test
(Zach_Prints, 2021 & ReadyPlayerThirty, 2020)

Table 3: Example Prints Shared by Users



Successful



Unsuccessful

Tolerance Test
(Weldishofer, 2019 & Seegers, 2023)



Successful



Unsuccessful

Bridging Test
(Zach_Prints, 2021 & UltiMaker, 2023)



Successful



Unsuccessful

Overhang Test
(Clayton 2018 & Griffiths, 2021)

Table 3 continued: Example Prints Shared by Users

Chosen Settings and Specifications

This test model will be printed on an Ender 3-Pro FDM printer, designed and manufactured by Creality (Figure 2). This model is an extremely popular choice for a 3D printer at the consumer level, and will be printing with a hardened steel 0.4mm nozzle. The CAD model will be prepared for print using the free to download Ultimaker Cura slicer software, which is one of the recommended software options for the Ender 3-Pro as both's functionality and complexity matches the same target audience of medium to high level 3D printing hobbyists. The chosen hotbed and nozzle temperature will be kept at the default recommended settings for the two filaments, and will only be changed if there are major issues with printing or adhesion.

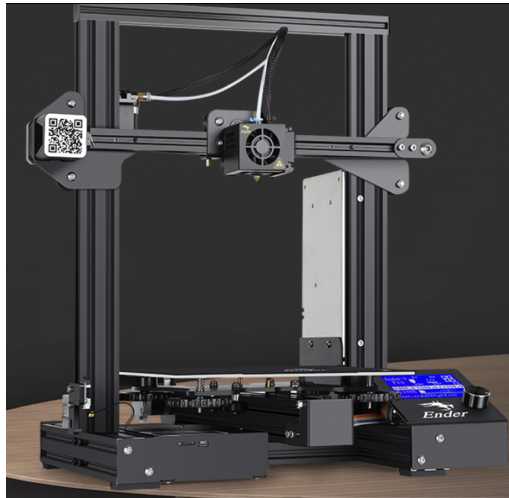


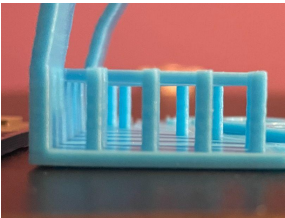
Figure 2: Ender 3-Pro
<https://www.creality.com/products/ender-3-pro-3d-printer>

Slicer Settings	
Model Scale:	100%
Quality:	0.16 mm
Infill:	40%
Print Speed:	50 mm/second
Wall Speed:	35 mm/second
Supports:	Off
Adhesion:	On
Estimated Printing Time:	3 hours 13 minutes
Filament Specifications	
Nozzle Temperature:	215°C
Bed Temperature:	60°C
Diameter:	1.75 mm ± 0.02 mm (Virgin PLA) 1.75 mm ± 0.05 mm (Recycled PLA)

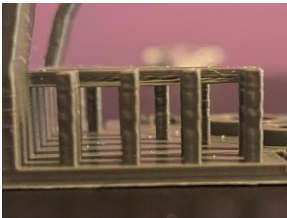
Table 4: Settings and Specifications

Results

Both prints were printed on the same day, by the same printer with no adjustments to printer settings made in between the prints. The prints were both done in a 19°C - 20°C and 36% - 37% humidity environment with the printer running at 100% fan speed.

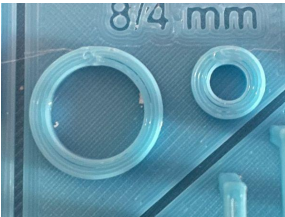


Virgin PLA

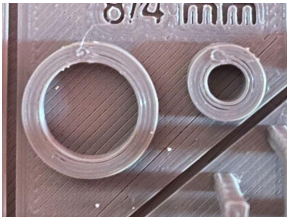


Recycled PLA

Stringing Test

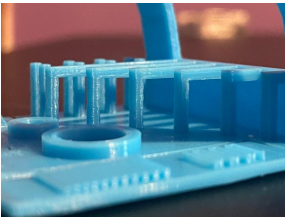


Virgin PLA

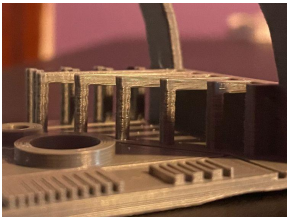


Recycled PLA

Scale/Diameter Test



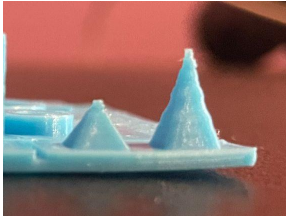
Virgin PLA



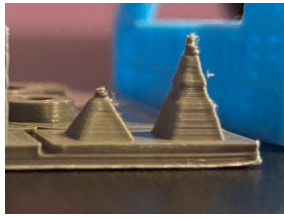
Recycled PLA

Bridging Test

Table 5: Comparison of the Virgin and Recycled PLA Prints



Virgin PLA

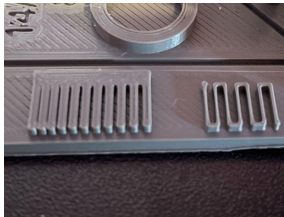


Recycled PLA

Sharp Corners Test



Virgin PLA



Recycled PLA

Tolerance Test



Virgin PLA



Recycled PLA

Overhang Test

Table 5: Comparison of the Virgin and Recycled PLA Prints

Tolerance and Detail

Overall both prints performed well in the tolerance test, recreating very thin lines and gaps without pieces merging together (Table 5). A greater difference in quality can actually be seen in the text-based tolerance section, which pushes the

abilities of the filament past just printing in straight lines (Figure 3). With the added curves, diagonals and filler space, the virgin PLA has cleaner gaps where the text is defined, as well as having a more solid, filled-in surface for the areas in between.



Virgin PLA



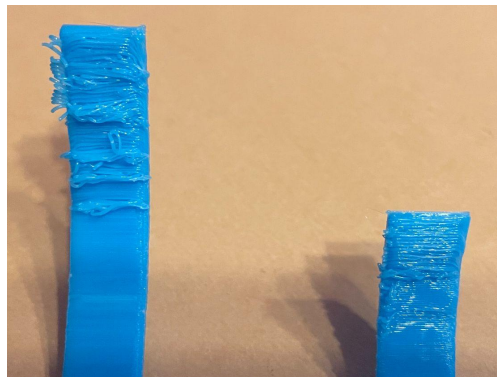
Recycled PLA

Figure 3: Comparison of the Text-Based Tolerance Tests

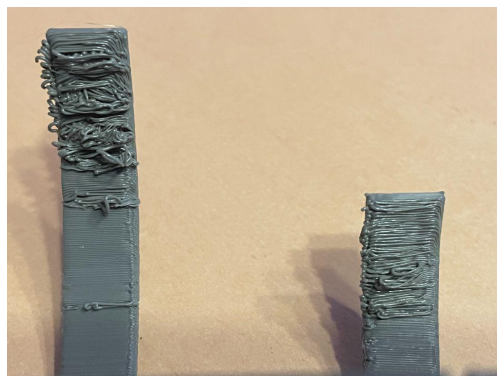
The sharp corners test was another area where the virgin PLA stood out in comparison to the recycled PLA. The virgin PLA not only has a smoother, more consistent build up to the top point of the pyramid shapes, but also has a cleaner top point itself, with less bulging and stringing (Table 5).

Overhangs, Bridging and Durability

Both the virgin PLA and recycled PLA prints handled the bridging tests quite well, spanning even the largest 2.5cm gap with no noticeable sagging or collapsing issues (Table 5). The difference between the filaments becomes more apparent in the overhang tests, where the virgin PLA outperformed the recycled PLA with a cleaner print surface (Figure 4). Both prints began to have sagging issues at the 60° angle, but the issues are much more prevalent on the recycled PLA print, where the overhang shape gets significantly messier in the 70°, 75° and 80° sections than what defects occur in the virgin PLA print. While overhang issues are often solved with the use of supports added to the print during the slicing process, ideally these are used as little as possible or only when necessary as the extra material and time required to carefully remove them adds up when producing many prints or prototypes.



Virgin PLA



Recycled PLA

Figure 4: Comparison of the Overhang Tests

While an official test of durability was not done in this study, it is notable that while handling both prints for measurements and photos, a break did occur on the recycled PLA print (Figure 5). Two of the pillars that made up the stringing portion of the Micro AIO test were snapped off accidentally while handling the print. A small amount of pressure was next put on the same pillars on the virgin PLA print in an attempt to recreate the break, but those pillars held steady. Having a low durability could impact prototypes that get transported or handled frequently and, if this result repeats, could discourage the use of the recycled PLA filament.

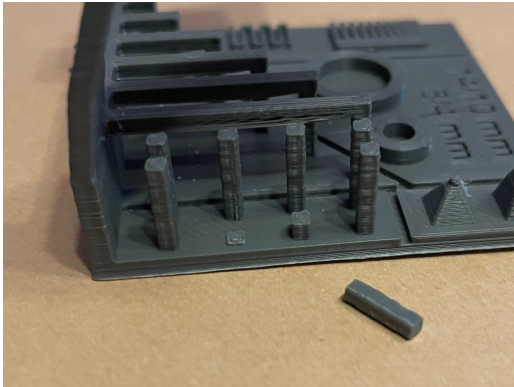
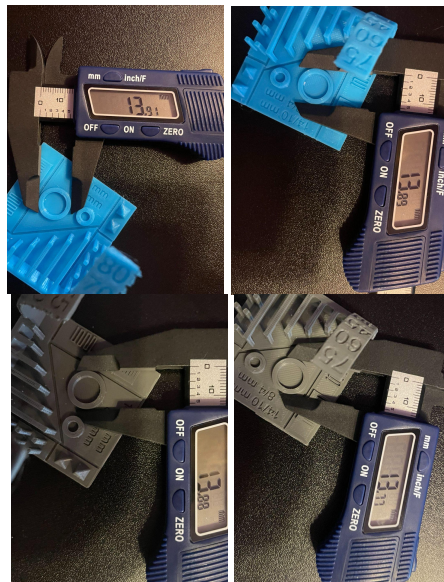


Figure 5: Broken Pillars on the Recycled PLA Print

Dimensional Accuracy

Likely the most important metric to determine if recycled PLA is suitable for use in prototyping is dimensional accuracy. From first visual inspection, both prints have no clear defects, look symmetrical in size and have good symmetry in the Micro AIO dimensional accuracy test. For more accurate inspection, a digital caliper was used to measure these dimensions (Figures 6 & 7).

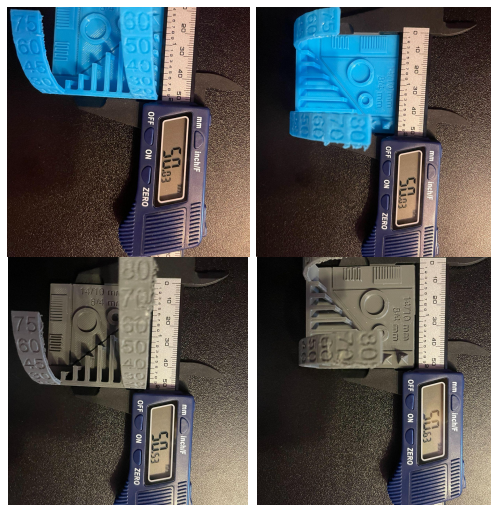
The virgin PLA has more consistent dimensions in both tests, having only a 0.02mm variation in the scale/diameter test and no variation in the overall size of the print. The recycled PLA print falls just slightly behind with a 0.11mm variation in the scale/diameter test and a 0.1mm variation in overall size.



Virgin PLA

Recycled PLA

Figure 6: Comparison of the Dimensional Stability Tests - Measured with a digital caliper in millimeters, at two points with 90° rotation.



Virgin PLA

Recycled PLA

Figure 7: Comparison of the Print Size - Measured with a digital caliper in millimeters, at two points with 90° rotation.

Discussion

Use of Recycled PLA

After analyzing the results of the test prints it can be seen that the recycled PLA did not quite perform up to the same standard as the virgin PLA filament. The most drastic variations occur in the dimensional accuracy and detail tests, which are very likely the most important factors when creating prototypes. If the colour accuracy or durability of the prototype was crucial to match the final product design, 3D printing would not be the recommended prototyping method for a company to use anyway. They would likely be advised to use the same material or fabrication process as the final product. However, if the 3D printed prototype was made to be accurate to the size and form of the final product, for example used to create packaging, the shape, dimensional accuracy and detail could be crucial and, based on the results of this study, virgin PLA does slightly outperform recycled PLA. The dimensional variation on the recycled PLA print is still less than a millimeter and could easily still be an option for prototypes that do not need to be extremely accurate.

Another study looking at the mechanical properties of recycled PLA filament also found the material to be less durable, with the main factor affecting this property being how many times the plastic had been recycled before. This study found that by the third time material was recycled, it had lost almost 40% of its original short-beam strength, a test that essentially describes putting pressure in the middle of a beam to test its bending properties before breaking (Lanzotti et al., 2019). The recycled PLA acquired from Filaments.ca had no indication how many times the material had been recycled before and furthermore, in the instructions for contributing consumer or industry waste to the recycling process, did not specify if already recycled PLA waste could be included in the drop-off (Filaments.ca, 2024). It is likely that users who are aware of and contribute to the recycling program have also bought recycled PLA from the supplier, so there is a high chance PLA that has already gone through the recycling process has ended up in the batch of filament used for these tests, and could in turn explain the fragility of the recycled PLA print.

Future Research Potential

While this study ran one test with one alternative filament option to fit into the time constraints of the semester, research on this topic would greatly benefit from more studies that examine other filament options and either run tests multiple times or run a greater variety of tests to confirm the results found here. Since recycled PLA is not the perfect solution for accurate prototype printing, or the perfect filament disposal method, as it can only be recycled a couple of times before material degradation begins to drastically affect quality, research in this area should not stop any time soon. Research on better composting methods of

PLA, or materials such as the filaments being developed from sugarcane or potato starch, would also be beneficial to 3D printing as a whole. From large companies to hobbyist printers, many would benefit if old material did not have to be taken to a specialized facility for proper disposal.

Another area of research that would be beneficial to be covered in the future would be examining the difference in life cycles of prototypes used in different industries. Research on this topic could answer questions such as which industries keep their prototypes for multiple uses, and which go through many temporary prototypes in their iterative design process? As well as, do specific industries differ in how accurate their prototypes need to be? This research could help determine where alternative materials should start being implemented, even if they are not yet up to the same standard as the traditional virgin PLA, ABS or PETG filaments.

Conclusion

Overall, using alternative materials rather than virgin plastics allows companies to both use 3D printing as a fabrication method for their prototypes and incorporate sustainable processes into their workflow. While more materials options, such as easily, or consumer biodegradable 3D printer filaments made from sugarcane or potato starch, are still in development, recycled PLA is a decent filament material with similar properties to virgin PLA. Differences between these two filament options are minor and only prototypes that need to be extremely accurate dimensionally or be as durable as possible should opt for the virgin PLA option. Additive manufacturing still presents itself as a sustainable alternative for prototype creation, as opposed to traditional subtractive methods such as milling that produce greater amounts of waste, so further research on alternative materials for this process, and how to get them up to the same dimensional stability and durability standard as virgin PLA, or further research on how to better recycle or compost PLA would be beneficial to many industries as the creation of iterative prototypes spans many different fields of work. So, despite the plastic waste currently produced by 3D printing materials, additive manufacturing technology is still a great option to invest in today for prototype creation, even for companies looking to increase their sustainable practices, as long as research and improvement in material and waste disposal options are continued.

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