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Research article

Evaluating Energy Consumption and Mechanical Properties of 3D Printing-Produced Parts with ABS, PLA, and PETG Plastic Materials

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A B S T R A C T

Unbalanced manufacturing activities lead to problems such as environmental deterioration, climate change, and natural resource depletion. To address the need for balancing energy consumption and mechanical performance, this study compares the total energy consumption, Young's modulus, and tensile strength of biodegradable plastic material PLA with those of petroleum-based thermoplastic materials ABS and PETG, at infill densities of 50%, 75%, and 100%. Statistical analyses indicate that the total energy consumption of PLA, including material production, 3D printing, and recycling stages, falls between that of PETG and ABS across all infill densities, while PLA exhibited the lowest energy consumption in the 3D printing process.

The findings also revealed that Young's modulus increased with increasing infill density for PLA, PETG, and ABS materials. The data showed differing tensile strength trends among the materials. While PETG and ABS exhibited increased tensile strength with increasing infill density, PLA's highest tensile strength is at 75% infill density, with only a slight increase observed at 100% infill density. This suggests that, for some PLA applications, a 75% infill density may provide adequate mechanical performance while reducing material and energy consumption, although additional experimental studies are needed to validate this finding.

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1. INTRODUCTION

The manufacturing sector is a major contributor to economic growth and societal wealth, generating high-paid jobs and societal wealth. With the worldwide rapid global industrialization and development, the manufacturing sector faces increasing pressure to adopt sustainable practices that help minimize environmental impacts, conserve natural resources, and promote a cleaner society. To address this challenge,

manufacturing leaders are recognizing this need and pursuing sustainable solutions through education, research and development (R&D), and technological innovation.

As a disruptive innovation fundamentally different from traditional manufacturing methods, which typically involve removing material from a large block, 3D printing builds objects using computer-aided design and manufacturing (CAD/CAM) technologies and depositing materials layer by layer, therefore also known as additive manufacturing (AM).

Due to its additive nature, 3D printing may open ways to contribute to sustainable production. Directly generating toolpaths using CAD/CAM technologies, 3D printing does not use physical tooling, thereby reducing energy consumption by eliminating energy-intensive tooling and simplifying overall manufacturing processes. Only depositing necessary materials in layers in 3D printing leads to less waste and higher material utilization compared to traditional subtractive manufacturing methods. 3D printing contributes to manufacturing sustainability with minimal raw material waste, conserving energy, and enhancing resource efficiency [1].

When 3D printing was introduced in the 1980s, it was developed for rapid prototyping with soft materials like liquid polymers and plastic powders, so engineers could use it to test product designs, evaluate component fits, and assess functionality before full-scale production. Today, 3D printing is widely used across various industries to produce functional end-use parts from strong materials, including metals, ceramics, and composites. According to Wohlers Associates [2], approximately one-third of 3D-printed parts are now used for functional applications. Customized tooth correction retainers and ceramic hip replacement components are good examples of 3D printing used in the medical field, and companies like Airbus, Boeing, Honeywell, and GM are exploring 3D printing's applications [3].

Despite its advancements, challenges remain in achieving the full potential of 3D printing for sustainability. For example, Joshi and Sheikh [3] highlighted its growing popularity in the aerospace industry, but also noted limitations regarding the types, quality, and variety of materials compatible with 3D printing. Apart from surface finish limitations and post-processing material removal requirements, another drawback is the relatively low material strength, since the vast majority of 3D-printed parts are still made from plastic materials. Mordor Intelligence [4] estimated roughly 72% of the entire 3D printing filament market is plastic, and this includes both hobbyist and industrial materials used in Fused Deposition Modeling (FDM) of Polylactic acid (PLA), ABS (Acrylonitrile Butadiene Styrene), PETG (Polyethylene Terephthalate Glycol), and Nylon. To address the issues of mechanical strength and sustainability performance in 3D printed parts, this research aims to evaluate the energy consumption and mechanical properties produced with PLA, ABS, and PETG, to balance these two performances.

The novelty of this research is the integrated evaluation of sustainability and mechanical performance for three most commonly used FDM 3D printing materials, namely, PLA, ABS, and PETG, under identical printing conditions and infill densities. Unlike previous studies that have primarily focused on either mechanical characterization or life cycle assessment independently, this study combines experimentally measured Young's modulus and tensile strength with total energy consumption, including for material production, 3D printing, and recycling stages, to assess the trade-off between structural performance and sustainability. Also, this study demonstrates that PLA specimens printed with 75% infill density exhibit tensile strength similar to 100% infill, indicating that significant material and energy savings can be achieved without losing mechanical performance for engineering applications. These findings help in selecting both material and infill density to improve the sustainability of FDM printing while obtaining required mechanical properties.

2. LITERATURE REVIEW

From its inception, plastics have been the default choice for 3D printing because they melt at much lower temperatures than metals or ceramics. The first 3D printing invention used stereolithography, in which liquid photosensitive polymer resins were hardened to form part geometry and structure under exposure to UV light. The 3D printing parts in

SLA are generally limited to being a visual prototype because they would easily warp or degrade under normal sunlight [5].

Compared to parts that are cured from polymer resins, ABS is a stronger plastic with better mechanical properties, such as impact resistance, toughness, rigidity, dimensional stability, and lightweight, and has therefore been widely used in the plastic molding process to fabricate a variety of functional products before the invention of 3D printing. Considered as low-cost, ABS is widely used in the fabrication of many products, such as toys, automotive interior components, protective helmets, and consumer product packages. After the FDM 3D printing was patented in 1989, which melts ABS plastic filament into formable paste and deposits in layers, ABS quickly became a popular 3D printing material for engineering applications, primarily because of its favorable mechanical properties, less strict operating requirements, and less environmental impact than the STL technology [6].

Although ABS demonstrates noticeable advantages over 3D-printed parts made from cured polymer resins, one disadvantage is its relatively weak interlayer bonding, which can reduce the mechanical strength of printed parts. As a result, ABS printing often requires a closed printing enclosure and careful temperature control [7]. Another drawback is that the 3D printing process using ABS tends to generate strong fumes, particularly during the early stages of printing; therefore, adequate ventilation is necessary to minimize its impact on the surrounding environment.

ABS has significantly improved warping, shrinkage, and sensitivity to UV light exposure compared to 3D parts produced by STL technology. The advancement of 3D printing technology has driven the search for more options of compatible or better materials. Showing strong interlayer bonding and leaving less internal stress in 3D printing parts, PETG stands for more desirable characteristics in comparison to the weak strength of ABS parts due to weak layer bonding [8]. PETG gained popularity in 3D printing since the mid-2010s, especially with the shift from large-size expensive enclosed 3D printers to desktop-size 3D printers, for both prototyping and functional parts or engineering applications.

ABS and PETG are thermoplastic materials derived from petroleum or crude oil. Because petroleum extraction and production rely on nonrenewable resources, continued use of ABS and PETG may contribute to resource depletion over time. Another prominent drawback of petroleum-based plastic materials is that they are nondegradable and can persist in the environment for centuries without breaking down into dissolvable small components. This brings significant sustainability issues recognized by the entire global community. For a long time, research attention has been focusing on finding environmentally friendly plastic alternatives to support economic development while conserving natural resources and reducing carbon footprint on the earth. Fundamentally different from ABS and PETG, PLA is a bio-based thermoplastic derived from renewable, organic materials like corn starch and sugarcane. PLA naturally degrades over time or in commercial composting facilities, reverting to its organic components without a toxic footprint on the earth. Due to its nontoxic nature, non-fuming smell, and degradability, PLA has become one of the widely used materials in FDM 3D printing among hobby players and educational institutions since the mid-2010s [9].

The mechanical properties of PLA are of a mixed nature, having the highest tensile strength among ABS and PETG, but being brittle, showing the lowest toughness, and not suitable to withstand sudden impact [9]. On one hand, PLA's low melting temperature indicates an advantage that PLA's printing temperature is relatively low compared to ABS and PETG, which requires lower energy, whereas a disadvantage is that parts made from PLA cannot endure high working temperatures or long-term UV light exposure. At around 60°C, PLA begins to soften, and PLA parts may lose their accurate, stable shape due to thermal deformation in a high thermal fluctuation environment. Even though PLA is a renewable bio-degradable plastic material, the production and usage of PLA still cause concerns because it is produced from food-related agricultural products, which may lead to food shortages. With the increasing awareness of sustainability, a lot of research has been conducted to evaluate the impact of these materials on sustainability.

The life cycle analysis (LCA) is a standardized method used to quantify the environment impacts of a product, service, or process across its entire lifespan. Ghomil et al. [10] conducted a literature review regarding the LCA for PLA from cradle to grave. Including the feedstock acquisition and conversion, production, application, and deposition, this study concluded that it is possible to make a low-carbon material by optimizing the conversion process, which is the most energy-intensive stage. Instead of using food as a ferment material, Senila et al. [11] conducted an LCA study of PLA produced from orchard waste and reported a similar result that the initial stages of biomass processing and pretreatment are the most energy-intensive and significant contributors to carbon emissions. The literature review by Fonseca et al. [12] noted that PLA is a solution to replace fossil plastics. However, the use of alternative biomass sources without competition with the feed and food sector could be a key option for biobased materials production, with lower environmental and socioeconomic impacts.

Kumar et al [13] performed a study on the LCA of a 3D printed product with PLA, ABS, and PETG materials, focusing on the comparisons of their environmental impacts from cradle to cradle, including four phases from raw material extraction, production, use, and recycling. This study examined eight environmental categories, namely, climate change, fossil depletion, freshwater ecotoxicity, human toxicity, ozone depletion, particulate matter formation, terrestrial acidification, and water depletion. This study reported that PETG material is found to be the most environmentally friendly across all parameters, and ABS is the least environmentally friendly, whereas PLA stays in the middle.

Fontana et al. [14] evaluated the energy consumption and mechanical properties of PLA plastic tensile bars that were 3D printed from self-produced filament and commercial alternatives, by varying infill percentage at 25%, 50%, 75%, and 100%, and varying layer height of 0.2mm and 0.3mm. The test revealed that the 0.3mm layer height consistently generated higher stiffness and tensile strength, and less energy consumption due to a faster deposition rate. The total energy that was required to print the tensile bars with PLA self-produced in-house is almost three times the energy used with commercial PLA. The experiment results indicate that self-produced PLA is not a viable option, and a scalable recycling and production of PLA filament will generate more consistent PLA filament and better energy efficiency.

Amrita et al. [15] investigated the mechanical properties of 3D printed PLA tensile bars by varying infill patterns with a single infill density 30%, and tensile strength is found to be highest for the hexagonal infill pattern and least for the line infill pattern, and toughness and hardness are found to be highest for the 3D infill pattern.

At normal room temperature, PLA, ABS, and PETG under tensile tests do not display a clear distinction between elastic deformation and plastic deformation because they fail quickly after reaching the elastic limit. Therefore, this research concentrates on comparing the sustainability performance regarding energy consumption and mechanical performance in terms of Young's modulus and tensile strength of 3D printing materials, namely, PLA, ABS, and PETG, by varying infill density at 50%, 75%, and 100%, to identify the balance between mechanical properties and sustainability.

3. RESEARCH METHOD, MATERIALS, EQUIPMENT, AND SAMPLE PREPARATION

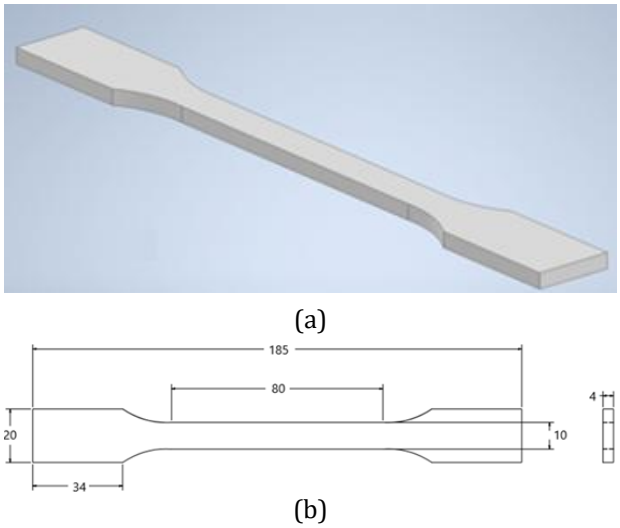
The total energy consumption reported in this study was not measured entirely through direct experimentation. Instead, it was calculated by integrating experimentally collected data with secondary data obtained from the literature. The experimentally measured data included the 3D printing time and deposited material weight for every printing condition. This is recorded directly from the PRUSA CORE One printer. The embedded energy associated with material production and recycling was obtained from the published study [13]. Using these literature-based energy values along with experimentally measured printing time, material mass, and the printer's average power consumption, the total energy consumption was calculated for each material and infill density. Therefore, the reported total energy consumption represents a hybrid analysis based on both experimental measurements and validated literature data rather than being measured entirely through direct experimentation.

- The CAD model of the plastic tensile testing specimens was created based on ASTM D638 (Standard Test Method for Tensile Properties of Plastics), shown in Figure 1.
- All testing samples of PLA, ABS, and PETG were printed using the PRUSA CORE One 3D printer, which comes standard with a 0.4mm nozzle diameter. The machine settings (nozzle temperature and bed temperature), along with the power consumption [16] is shown in Table 1. All samples were 3D printed using a rectilinear infill pattern with a layer height of 0.15 mm and an infill speed of 140 mm/s. Five tensile bars were printed in a batch for one experimental treatment, and a total of 45 tensile bars in nine batches were printed. The 3D printing time and deposited mass data were collected from the 3D printer's operating software interface, shown in Figure 2. To help understand the analysis of total energy consumption, the data collected is presented in Section 4.2.

Table 1. Printing thermal data and power consumption for PLA, ABS, and PETG

	Nozzle Temperature	Bed Temperature	Power Consumption while 3D printing
PLA	215°C	60°C	90W
PETG	230°C	85°C	115W
ABS	255°C	100°C	120W

- The tensile specimens were tested in a Shimadzu universal testing machine. The machine, along with a loaded sample, is shown in Figure 3(a), and a sample after testing in Figure 3(b). The tensile test in Shimadzu is fully automated, except for loading and unloading the sample. The software simultaneously records data and displays the strain-stress curve throughout the testing process until fracture failure occurs.
- All tests were performed at room temperature, about 20°C, and the stress-strain curves of all specimens showed almost no plastic deformation region. One example of the test stress-strain curve exported from the Shimadzu machine is displayed in Figure 4.



(a)

(b)

Fig. 1. (a) Plastic tensile testing bar model and (b) Tensile test bar defined by ASTM D638.

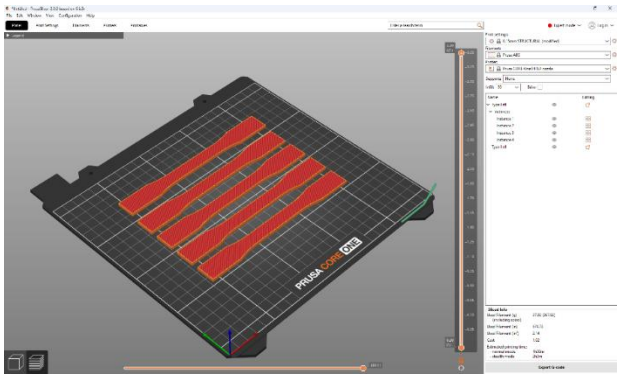
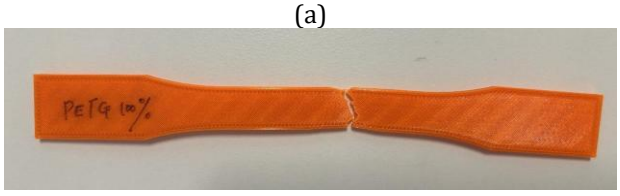


Fig. 2. Software interface to collect data for PRUSA CORE One 3D printer.



(a)



(b)

Fig. 3. (a) Shimadzu tensile testing machine with a loaded sample. (b) PETG test sample with 100% Infill density.

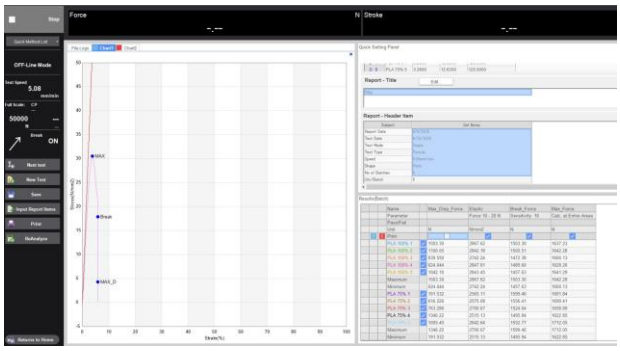


Fig. 4. Tensile testing output.

4.1 Mechanical properties comparisons of the tensile bars 3D printed in PLA, ABS, and PETG

The raw output of the tensile tests includes Max_Desp_Force, Elastic Force, Break_Force Sensitivity, and Max_Force.

The Max_Disp_force stands for Force at Maximum Displacement. It is the pulling force (measured in Newtons) recorded by the machine at the very final moment of the test, right when the crosshead reaches its furthest point of travel stroke, which matches the last data point on the stress-strain curve. Because plastics stretch and weaken before they snap, the force at the maximum displacement is always significantly lower than the peak force. Break Force Sensitivity, sometimes called *Break Detection Sensitivity*, is a software setting that monitors the machine exactly when to stop the test and look for the final break. It is a threshold value, usually set as a percentage (e.g., 80%) or a specific force drop (e.g., 5 N), which defines how sudden a drop in force the software identifies as the fracture point and stops applying forces. Setting too high or low sensitivity mistakenly may lead to false recording of elongation.

The data of Elastic Force is recorded in Newton per mm^2, and it is the testing material's Young's modulus, indicating the slope of the stress-strain, shown as the red line. The recorded Maximum Force in Newton was converted to tensile strength in Newton per mm^2 by dividing the cross-sectional area, matching the highest point of the stress-strain curve. Table 2 presents the Young's modulus and tensile strength values for PLA, ABS, and PETG under different infill densities.

Table 2. Mechanical properties from the tensile test.

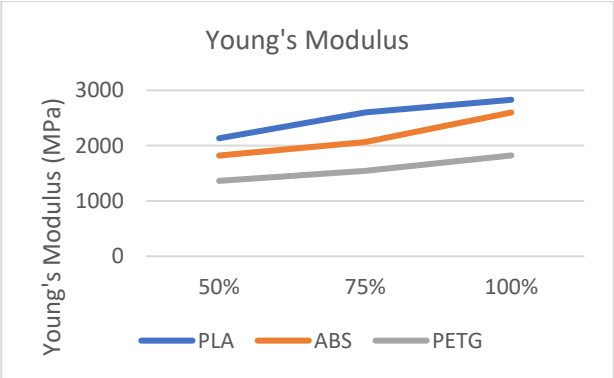
	Young's Modulus	Max_Force	Tensile strength
	N/mm^2 (MPa)	N	N/mm^2(MPa)
PLA 100% 1	2867.62	1637.23	39.76388
PLA 100% 2	2842.18	1642.28	39.88653
PLA 100% 3	2742.24	1600.13	38.86282
PLA 100% 4	2847.81	1628.26	39.54602
PLA 100% 5	2843.45	1641.29	39.86249
PLA 75% 1	2565.11	1691.84	41.09021
PLA 75% 2	2575.08	1699.41	41.27406
PLA 75% 3	2700.67	1658.89	40.28994
PLA 75% 4	2515.13	1622.85	39.41463
PLA 75% 5	2642.64	1712.05	41.58105
PLA 50% 1	2013.44	1278.98	31.06296
PLA 50% 2	2141.62	1308.76	31.78623
PLA 50% 3	2188.05	1290.52	31.34323
PLA 50% 4	2146.24	1271.28	30.87595
PLA 50% 5	2175.49	1204.07	29.2436
ABS 100% 1	2600.44	1481.64	35.98502
ABS 100% 2	2501.1	1382.32	33.57281
ABS 100% 3	2634.14	1477.04	35.8733

ABS 100% 4	2654.12	1481.21	35.97458
ABS 100% 5	2605.16	1481.21	35.97458
ABS 75% 1	2127.55	1033.78	25.10771
ABS 75% 2	2046.84	1040.17	25.26291
ABS 75% 3	2049.06	1040.18	25.26315
ABS 75% 4	2018.59	1037.78	25.20486
ABS 75% 5	2078.8	1033.31	25.0963
ABS 50% 1	1787.43	943.893	22.9246
ABS 50% 2	1837.13	952.403	23.13129
ABS 50% 3	1826.81	974.169	23.65992
ABS 50% 4	1820.57	955.951	23.21746
ABS 50% 5	1831.22	954.175	23.17432
PETG 100%	1837.04	1695.58	41.18104
PETG 100%	1796.02	1684.74	40.91777
PETG 100%	1799.4	1607.96	39.05299
PETG 100%	1839.06	1662.23	40.37106
PETG 100%	1839.68	1636.81	39.75368
PETG 75% 1	1584.49	1427.11	34.66063
PETG 75% 2	1549.66	1446.8	35.13885
PETG 75% 3	1501.57	1427.09	34.66015
PETG 75% 4	1558.09	1397.94	33.95217
PETG 75% 5	1521.53	1408.96	34.21982
PETG 50% 1	1304.11	1196.79	29.06679
PETG 50% 2	1355.47	1255.24	30.48638
PETG 50% 3	1392.61	1269.03	30.8213
PETG 50% 4	1358.47	1257.21	30.53422
PETG 50% 5	1403.6	1255.68	30.49706

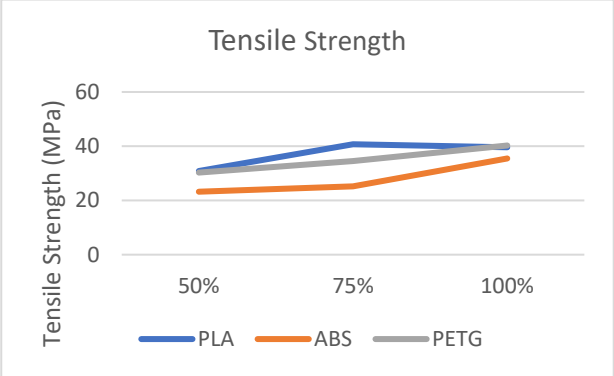
The average test results for each experimental condition, using PLA, ABS, and PETG at infill densities of 50%, 75%, and 100%, are summarized in Table 3 and plotted in Figure 5. Figure 5 (a) shows that Young's modulus increases with the increase of material infill density for PLA, PETG, and ABS, and at every infill density level, PLA is the highest, ABS the lowest, and PETG in the middle. Figure 5(b) shows that, unlike PETG and ABS, whose tensile strength increased with infill density, PLA exhibited the highest tensile strength at 75% infill density, with a slightly lower value at 100% infill density. This may suggest that it may be possible to use 75% infill density, instead of 100% for some applications, for 3D printing filament deposition, thereby saving material and energy consumption. Another possible impacting factor could be the filament used for the batch of Infill density 75% and the batch of Infill density 100%. Since the 3D printer ran out of filament during the experiment, a new filament roll had to be inserted, which may have influenced the PLA results.

Table 3. Average value of Young's Modulus and Tensile Strength.

	Y's modulus			Tensile Strength		
	PLA	ABS	PETG	PLA	ABS	PETG
50%	2132.97	1820.63	1362.85	30.86	23.22	30.28
75%	2599.73	2064.17	1543.07	40.73	25.19	34.53
100%	2828.66	2598.99	1822.24	39.58	35.48	40.26



(a)



(b)

Fig. 5. Young's modulus and tensile strength for PLA, ABS and PETG samples.

Further, using SPSS software, a two-way ANOVA analysis was conducted to compare the differences of Young's Modulus and tensile strength caused by different experimental conditions and the outputs are displayed in Tables 4 and 5. All p-values reported as <0.001 in the ANOVA Table 4 and 5 show that both the material types and Infill density levels and their interactions are all significant in generating the differences in Young's modulus and tensile strength because the p-values are all smaller than 0.05, the normal cutoff value.

A separate comparison was conducted for the tensile strength of PLA at different infill density levels because the tensile strength at 75% infill density was unexpectedly higher than that at 100% infill density. The multiple mean comparison shown in Table 6 reveals that tensile strength at 50% infill density is significantly different from that at 75% and 100%, but the difference at 75% and 100% is not significant. The similar tensile strengths suggest that, within the infill density range of 75% to 100%, lower-density 3D printing may be suitable for certain applications in which mechanical strength is not a primary concern, thereby reducing material consumption. To verify this finding, more data should be collected in future experiments by varying the infill density levels at 70%, 80%, 90%, and 100%.

Table 4. Tests of Between-Subjects Effects (Young's Modulus).

Dependent Variable: Young's Modulus						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	10195046.730[a]	8	1274381	542.008	<.001	0.992
Intercept	1.96E+08	1	2E+08	83275.1	<.001	1
Material	6816873	2	3408437	1449.64	<.001	0.988
Density	3121612	2	1560806	663.827	<.001	0.974
Material * Density	256561.7	4	64140.4	27.28	<.001	0.752
Error	84644.05	36	2351.22			
Total	2.06E+08	45				
Corrected Total	10279691	44				
a. R Squared = .992 (Adjusted R Squared = .990)						

Table 5. Tests of Between-Subjects Effects (Tensile Strength).

Dependent Variable: Tensile_Strength						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1658.726[a]	8	207.341	411.113	<.001	0.989
Intercept	50041.36	1	50041.4	99221.4	<.001	1
Material	683.755	2	341.878	677.87	<.001	0.974
Density	798.689	2	399.345	791.816	<.001	0.978
Material * Density	176.281	4	44.07	87.382	<.001	0.907
Error	18.156	36	0.504			
Total	51718.25	45				
Corrected Total	1676.882	44				
a. R Squared = .989 (Adjusted R Squared = .987)						

Table 6. Multiple Comparisons of tensile strength with infill density.

Multiple Comparisons[a]						
Dependent Variable: Tensile_Strength						
Tukey HSD						
(I) Infill Density	(J) Infill Density	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
100%	75%	-1.14563	0.50141	0.097	-2.4833	0.1921
	50%	8.72195*	0.50141	<.001	7.3843	10.0597
75%	100%	1.14563	0.50141	0.097	-0.1921	2.4833
	50%	9.86759*	0.50141	<.001	8.5299	11.2053
50%	100%	-8.72195*	0.50141	<.001	-10.06	-7.3843
	75%	-9.86759*	0.50141	<.001	-11.205	-8.5299
*. The mean difference is significant at the 0.05 level.						
a. Material Type = PLA						

4.2 Energy Consumption for 3D Printed Tensile Bars

The power consumption rate of the PRUSA CORE ONE 3D printer varies at different working stages. According to Prusa Research's machine data sheet, its power consumption peaks at the initial printing bed warm-up stage at about 220 to 325 W, while idle time is at about 13 to 15W (Prusa Research, n.d.). Due to differences in melting temperatures, the average power consumption of 3D printing for PLA is lower than that required for PETG and ABS. The PRUSA CORE One's power consumption rate is given as a range in the machine data sheet, and the average value is chosen for this research: PLA 90W, 115W for PETG, and 120 W for ABS (Listed in Table 1). In this study, only the energy consumed during the 3D printing process was considered. Energy usage in idle time and print-bed warm-up was excluded from the analysis.

The essential data for comparing the three plastic materials are either found from secondary data through literature review or through experimental investigations. Referring to literature [13] that extracted energy data from Umberto NXT's Eco-invent 3.01 database and compared a 3D printed soap box including an inside filter with PLA, ABS, and PETG, the embedded energy data, including both manufacturing and recycling phases for the three plastic filaments, is listed in Table 7. Table 8 presents the recorded 3D printing time and deposited material mass for five sample pieces, collected from 3D printer PRUSA CORE One' software. Using data in Table 7 and 8, and the average power consumption rate data presented above 90W, 115W, and 120W, respectively, the total energy consumption for 3D printing the samples is calculated by using equations (1), (2) and (3). The calculation result is listed in Table 9.

$$Embedded\ energy\ (Kwh) = Embedded\ energy\ \left(\frac{Kwh}{g}\right) \times Mass\ printed\ (g) \quad (1)$$

$$Printing\ energy\ (Kwh) = Power\ consumption\ rate\ (Kw) \times Printing\ time\ (hour) \quad (2)$$

$$Total\ energy\ (Kwh) = Embedded\ energy\ (Kwh) + Printing\ energy\ (Kwh) \quad (3)$$

For example, 43.54 grams of PLA (in Table 8) were used for printing five tensile bars in one hour and 50 minutes with 50% Infill density. PLA's embedded energy is 0.041791 Kwh/g (in Table 7), PLA's printing power consumption rate 90W, and the total energy used is 1.9846Kwh (in Table 9), which includes 1.8196 Kwh (in Table 9) with producing and recycling PLA material, and 0.165 Kwh (in Table 9) with 3D printing.

Table 7. Data for material and energy consumption [13].

Materials	Material consumption (g)			Manufacturing Phase Energy Consumption (KWh)	Recycling Phase Energy Consumption (KWh)	Total Energy consumption (KWh)	Energy consumption per unit mass (KWh/gram)
	Filter	Soap Box	total				
PLA	13.59	50.3	63.89	0.50	2.17	2.67	0.041791
ABS	11.00	42.59	53.59	0.80	2.67	3.47	0.064751
PETG	13.92	51.51	65.43	0.67	1.70	2.37	0.036222

Table 8. Printing time and deposited material mass for five tensile bars with PLA, ABS and PETG.

	Printing Time (hour: minute)			Printing Time (hour)			Printing material mass (gram)		
	PLA	ABS	PETG	PLA	ABS	PETG	PLA	ABS	PETG
50%	1:50	1:50	1:50	1.833	1.833	1.8333	43.54	37.92	44.59
75%	2:00	2:01	2:01	2.000	2.017	2.0167	48.72	42.44	49.91
100%	2:05	2:05	2:06	2.083	2.083	2.1000	52.02	45.3	53.28

Table 9. Energy consumption for 3D printing five tensile bars with PLA, ABS and PETG.

	Embedded Energy (Kwh)			Energy Consumed in 3D printing (Kwh)			Total Energy Consumption (Kwh)		
	PLA	ABS	PETG	PLA	ABS	PETG	PLA	ABS	PETG
50%	1.8196	2.4554	1.6151	0.1650	0.2200	0.2108	1.9846	2.6754	1.8260
75%	2.0360	2.7480	1.8078	0.1800	0.2420	0.2319	2.2160	2.9900	2.0398
100%	2.1739	2.9332	1.9299	0.1875	0.2500	0.2415	2.3614	3.1832	2.1714

Data in Table 9 are plotted in Figure 6, which shows that energy consumed in 3D printing is only a small portion of the total energy consumed, at about 8% for PLA and ABS and 11% for PETG. Without considering the material embedded energy in the phases of manufacturing and recycling, 3D printing parts with PLA consumed the least energy, followed by PETG and ABS. When including the material embedded energy, Parts 3D printed with PLA stayed in the middle, higher than PETG but lower than ABS. Since the five samples were produced in the same batch, experimental data, such as material mass and printing time, for individual tensile bars were not available; therefore, the statistical comparison of energy consumption under different treatment conditions cannot be performed.

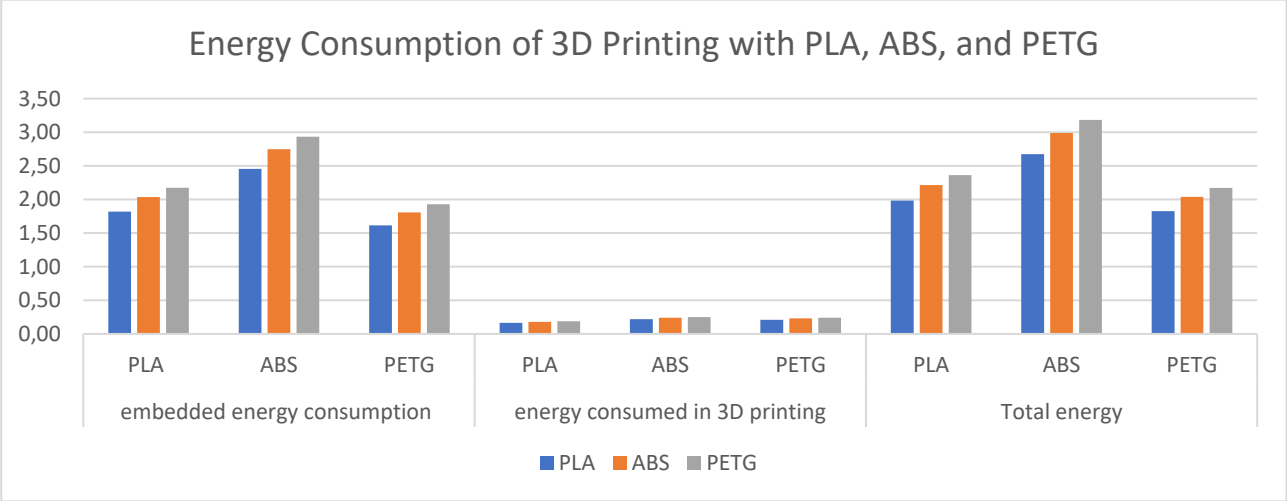


Figure 6. Energy consumption in 3D printing parts with PLA, ABS, and PETG at varied infill density

5. CONCLUSION

About four decades ago, the Brundtland Commission introduced the concept of sustainable development, defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [17]. Specifically, sustainability can be further defined as ensuring that the environmental impacts of manufacturing activities remain within the environment's natural self-recovery capacity, and is supported by the integration of the balanced three pillars' developments in economic, social and environmental aspects. Sustainable manufacturing is a multidisciplinary approach to manufacturing products using processes that are environment-friendly, conservative in consuming energy and natural resources, and safe for employees, consumers, and society as a whole.

Considering the constraints of plastic materials derived from petroleum that may be depleted

in the future, and also seeing the sustainability potential of biodegradable plastic materials, this research conducted an experimental study and compared the mechanical properties and energy consumption of tensile testing bars that are 3D printed in PLA, ABS, and PETG at three infill density levels, 50%, 75%, and 100%. Following the ASTM D638 standard test method for Tensile properties of plastic, 9 batches with each batch 5 samples, a total of 45 specimens were produced and tested at room temperature. The statistical analysis of the experimental data is summarized below:

- The Young's modulus increased with increasing infill density from 50% to 100% for all three materials. PLA showed the highest Young's modulus, ABS was intermediate, and PETG showed the lowest values.
- The tensile strength increases for ABS and PETG with the increase of infill density from 50% to 75% and 100%, while the tensile strength for PLA is lowest at 50%, but slightly higher at 75% compared at 100%, however, the difference of tensile strength at 75% and 100% is not significant.
- The energy consumption comparison shows that material embedded energy in manufacturing and recycling for PLA is between ABS and PETG, the energy consumed in 3D printing for PLA is the least amount. The total energy consumption, including that associated with material production, recycling, and the 3D printing process itself, was lowest for PETG tensile specimens, indicating its overall advantage.
- When considering degradability, renewability, and product strength, PLA is a better option because of its highest tensile strength, highest stiffness in terms of highest Young's modulus, and moderate total energy consumption.
- The experimental data also show that there is no significant difference in tensile strength between 75% and 100% infill densities. This suggests that, for certain applications, 75% infill may be a viable substitute for 100% infill, thereby reducing material usage and overall energy consumption. However, this is a preliminary finding that requires further validation.
- This data analysis also suggests that infill density levels should be further investigated by collecting additional data at 70%, 80%, 90%, and 100% to identify the optimal infill density that balances mechanical strength and energy consumption.

6. LIMITATIONS

- The actual electrical energy consumption during printing was not directly measured using a power meter.
- The study considers only three FDM materials (PLA, ABS, and PETG), limiting the generalizability of the conclusions to other materials.
- Only three infill density levels (50%, 75%, and 100%) and a single infill pattern (rectilinear) were investigated.
- The energy analysis excludes idle machine energy and bed warm-up energy
- Printing power consumption values are taken as average constant values

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