Research Article

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Developing Filament Extruder and Characterization of Recycled High-Density Polyethylene for 3D Printing Filament Material

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Abstract
With the rise of additive manufacturing, the demand for 3D printing feedstock has increased exponentially and its sustainability is critical in the future. Many scholars are now concerned about how 3D printing filaments should be reproduced from recycled plastic. This study aimed to develop a filament extruder machine and investigate the potential of using recycled high-density polyethylene (HDPE), one of the most commonly used and recyclable thermoplastic, for 3D printing filament material. Desktop sized filament extruder machine was built, and a smooth and round-shaped 1.75±0.01mm diameter recycled HDPE filament was produced. Its mechanical, thermal, chemical, and physical properties were characterized by conducting various tests and validation test was conducted by comparing its properties with its virgin counterpart. The ultimate tensile strength of the recycled HDPE filament was obtained 19.02±0.35MPa, which is comparable to the ultimate tensile strength of virgin HDPE, making it a viable 3D printing feedstock for rapid prototyping. According to Thermogravimetric analysis (TGA), the recycled HDPE filament offers significant thermal stability with an onset degradation temperature of 430℃ and a full degradation temperature of 520℃. Its Fourier Transform Infrared (FTIR) spectrum shows the same functional groups as virgin HDPE polymer. The recycled HDPE filament has also excellent water-rejecting capability. In general, the study revealed a promising result for the use of recycled HDPE plastic as a more sustainable and environmentally friendly source material for 3D printing filament. To increase the potential and market competitiveness of recycled filaments, further investigation is required to optimize the filament extrusion and 3D printing process parameters, improve the mechanical properties, and overall development methods for both the recycled HDPE filament and 3D printed products.

Keywords: Recycling, Additive Manufacturing, Extrusion, 3D Printing Filament

1. Introduction
Additive manufacturing, also known as 3D printing, is a process of making three-dimensional solid objects from a digital file. The creation of a 3D-printed object is achieved using additive processes, where successive layers of material are laid down in different shapes under computer control [1–4]. 3D printing is the opposite of subtractive manufacturing, which involves cutting away excess materials to create an object [4]. Additive manufacturing has become an increasingly popular method for producing complex and custom products within various industries including automotive, aerospace, biomedical, architecture, agriculture, and others. This innovative process allows for the creation of intricate designs while reducing waste and improving overall efficiency. Moreover, the advancements in additive manufacturing technology have made it more accessible and affordable for businesses to adopt. As a result, this manufacturing method is revolutionizing the way products are designed, developed, and ultimately brought to the market [2, 5, 6].

There are several types of additive manufacturing technologies available today. The most widely used techniques are stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), and selective laser melting (SLM). However, the most popular and cheapest form of AM technology is the FDM printer [7, 8]. The FDM process involves the extrusion of a thermoplastic filament through a heated nozzle, which is then deposited layer by layer onto a print bed to create the desired 3D object. The most widely used thermoplastic materials are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). In recent years, there has been an increase in filament types with different properties [9]. Many new and novel materials are also used in FDM like nanocomposites, ceramics, and biopolymers [7].

The 3D printing market is growing at a rate of 26% per year, and the potential of 3D printing technology to enhance the global economy has sparked a lot of interest and excitement [10]. With the rise of 3D printing, there is a high demand for 3D printing feedstock, with about 2 million metric tons utilized in 2013 and its sustainability is critical in the future [11, 12]. Although FDM 3D printers are becoming more and more affordable, the cost of the filaments for FDM 3D printers is prohibitively expensive and their accessibility is low in developing countries. With the rise of additive manufacturing technology, many scholars are concerned about how 3D printing filament can be reproduced from recyclable plastic which offers a sustainable and cost-effective alternative to commercial 3D printing filament [13-15].

Plastic recycling is the optimum option in the circular economy for handling post-consumer plastics to overcome environmental contamination, ensure sustainability and preserve natural resources for future generations. Distributed recycling of plastic in which consumers recycle their waste saves energy for transportation and reduces energy demand as compared to traditional recycling [13, 16–19]. One of the promising methods for distributed plastic recycling is to upcycle waste thermoplastic into 3D printing feedstock using a recyclebot, which is an open-source waste plastic extruder [16, 19, 20]. The filament extrusion involves heating, melting, and extruding thermoplastic materials into a continuous filament. The major components of the extruder are the extrusion screw, the barrel, the hopper, the die, and the transmission system. The extrusion screw, driven by an electric motor, is used to convey the raw material (in the form of pellets) from the hopper through the heated barrel. The molten thermoplastic is then passed through a die and molded into the desired shape and size. As the filament cools and solidifies, it retains this precise form, making it suitable for application 3D printing. The extrusion process relies on a combination of thermal energy and mechanical force, ensuring consistency in the filament's dimensions and quality. Throughout this procedure, precise control of temperature, pressure, and extrusion speed is crucial to producing a high-quality filament that meets the required specifications.

Earlier studies on distributed post-consumer plastic recycling with recyclebot revealed a 90% reduction in the embodied energy of the filament throughout mining, processing, and synthesis when compared to conventional production [21, 22]. The recyclebot also provides consumers with the chance to recycle plastic at home to offset the cost of purchased filament and make financial savings [16, 19–22]. Among recyclable thermoplastics, high-density polyethylene (HDPE), is used in a wide range of applications due to its high strength-to-density ratio, excellent toughness, and stiffness properties. It is widely used for milk and yogurt bottles, jerrycans, pipes, shampoo bottles, chemical drums, children's toys, bags, cable insulation, household and kitchenware, and others. Millions of tons of post-consumer HDPE waste are produced due to the wide range of applications in consumer goods, and pipes [23, 24]. Baechler et al [20]. produce HDPE filaments using a RecycleBot and establish a proof-of-concept for recycling high- value plastic wastes. During a life cycle analysis of recycling HDPE using a RecycleBot for 3D printing filament, Kreiger MA et al [21]. showed that distributed recycling uses 80% less energy than conventional recycling due to significant reductions in embodied energy for collection and transportation.

In this study, a cost-effective and user-friendly filament extruder machine was developed and used to produce recycled HDPE 3D printing filament. Several physical characterizations were conducted to assess the viability of utilizing recycled HDPE plastic as source material for 3D printing feedstock. The result revealed the viability of using recycled HDPE as source material for 3D printing feedstock. The filament extruder will allow for the production of tailored 3D printing filament in the lab for further investigations of novel materials applications in FDM 3D printing. Furthermore, it has major implications for distributed plastic recycling in the lab, workplace, or home. This will help to advance the use of recycled post-consumer plastics as a more sustainable and eco-friendly filament material to meet the high demand for plastic feedstock for the rapidly growing 3D printing industry. The results of this study will also serve as a guide and a source of reference for future research opportunities.

2. Materials and Methods

2.1. Materials

Distributed recycling of plastic waste becomes a strategy for improving material sustainability for the rapidly expanding 3D printing technology. It has great significance for reducing environmental pollution and the use of finite fossil-based natural resources. For this investigation, a variety of post-consumer HDPE plastic products such as shampoo bottles, detergent containers, milk bottles, and household bottles were collected based on their resin identification number (i.e., #2) to separate them from other polymers. The labels and attached glue stains were removed by hand peeling and using a wire brush, and the plastics are then washed using water to avoid contamination. The cleaned HDPE plastics were cut into rectangular strips with tin snip scissors and shredded with a rotor beater mill.

To achieve uniform flake size, the flakes were sieved using a 5mm filter. The shredded HDPE plastic flakes were then granulated using a granulating machine at a local recycling company at Bahir Dar. and recycled HDPE pellets were produced as shown in Fig 1 (a). The recycled HDPE pellets were dried in an oven overnight at 60°C which is below the glass transition temperature of the HDPE polymer (110°C) to remove any remaining moisture that could impair the extrusion process as shown in Fig 1 (b) below.

(a) **(b)**

Figure 1: Recycled HDPE pellets (a) and drying in an oven (b)

2.2.Design and Construction of Filament Extruder

2.2.1. Extrusion Screw

The purpose of an extrusion screw is to convey the polymer pellet through the heated barrel, mix it to a suitable molten state, compress it to an appropriate density, and force the extrudate into the nozzle. A complete analysis of the design of the compression-type screw with geometric parameters, as shown in Figure. 2. was conducted.

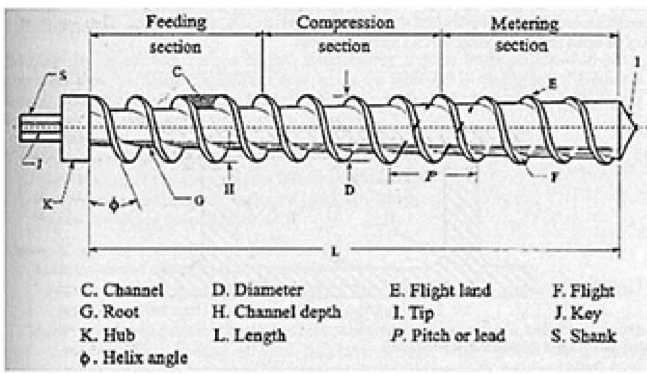


Figure 2: Detail geometrical parameters of a compression-type screw [25]

1) **Diameter and Length to Diameter (L/D) Ratio:** The objective of this study is to design and build a desktop-size filament extruder machine and hence the screw has to be the smallest possible size that can afford its purpose efficiently with a reasonable price. Considering this, a 20mm diameter screw was selected to work with precise usefulness and optimum price. For a typical screw, the L/D ratio generally is found between 20:1 to 34:1. The ratios can be increased based on different applications. The longer the L/D ratio, the lower the price. Taking this into account, an L/D ratio of 20:1 was selected. The flight length of the screw can be calculated from the L/D ratio: $L = 20 \times D = 20 \times 20 = 400$ mm. Therefore, the first parameters of the screw were determined with a diameter of D = 20mm, and a length of L=400mm.

2) **Pitch and Helix Angle of Screw:** The pitch of the screw (P) is the distance between the front of one flight and the same place on the next flight. For general-purpose screws, the pitch (P) is usually the same length as the diameter. As

a result, the pitch of the screw is taken as 20mm. The helix angle is the angle formed between the transverse plane of the screw and the screw thread. It can be determined as:

$$\emptyset = \tan^{-1}\left(\frac{P}{\pi D}\right) = \tan^{-1}\left(\frac{20}{20\pi}\right) = 17.7° \qquad (1)$$

3) **Flight Width:** The outside diameter of the screw flights will offer a balance between heat development and backward leakage if the flight width is maintained at 0.12 times the outer diameter of the screw. Hence, flight width,

$$W = 0.12 \times D = 0.1 \times 20 = 2.4 \text{ mm} \qquad (2)$$

4) **Channel Depth and Compression Ratio:** The screw's outer diameter never changes, but the root diameter varies along its length, resulting in a varied channel depth from the feed section to the metering section. The compression ratio is the ratio of the feed zone channel depth to the metering zone channel depth. It specifies how much pressure will be applied to the material as it passes from the feed zone through the transition zone, and into the metering zone. Compression ratios for general purposes typically vary from 2.2:1 to 2.8:1 To extrude various types of polymers via the extruder, a conservative compression ratio of 2.5:1 was chosen. The channel depth of the metering zone (Hm) can be calculated as

0.1 times the outer diameter of the screw.

$$H_m = 0.1 \times \square = 0.1 \times 20mm = 2\text{mm} \quad (3)$$

Based on the metering zone flight depth, the compression ratio can be utilized to determine the flight depth (Hf) in the feed section.

$$\text{Compression ratio, } CR = \frac{H_f}{H_m} = 2.5, \quad \text{Hence, } H_f = 2.5 \times 2mm = 5mm \quad (4)$$

5)**Flight Clearance:** Flight clearance also known as screw clearance is a measure of the space between the outer diameter of the screw thread and the inner surface of the barrel wall. The performance of the screw is negatively affected by improper flight clearance. A small clearance results in excessive wear on the screw flights, whereas a wide clearance reduces the screw's ability to melt material effectively. It is ordinarily taken to be 0.1% of the screw diameter.

$$\delta = 0.001 \times D = 0.001 \times 20 = 0.02\text{mm} \quad (5)$$

CAD model of the extrusion screw: Based on the above dimensions and information, the 3D CAD model of the extrusion screw is done on SOLIDWORKS 2020 software as shown in Fig 3.

Figure 3: CAD model of a three-zone compression screw

The screw must be hard enough to withstand high temperatures due to the heating system and the friction against the barrel. The melting temperature of polymer materials is lower and hence the recommended material for the screw is galvanized steel that has been dipped in a protective zinc coating due to its strong corrosion, and abrasion resistance, which withstands higher temperatures, and results in long service life.

The compression screw can be manufactured using a computer numerical control (CNC) lathe powered by a milling attachment to replace the tool post by plain turning, facing, threading, and grinding operations. It is expensive and the potential to manufacture the screw here was beyond the available resource. The solution to the problem was to buy a screw that would meet the functional requirements of the extrusion. For this investigation, a commercial auger bit can build up enough pressure at the nozzle. Looking at different commercial auger bits, a wood bore auger bit with a 20mm diameter and 450mm length (flight length of 380mm and shank length of 70mm, and shank diameter of 12mm) shown in Fig. 4 was bought and used.

Figure 4: Wood auger drill bit (Mikita brand) with a coupler attached at the shank

2.2.2. Barrel

The barrel is a hollow cylindrical chamber that provides housing for the screw and transfers the heat from the heating element to the material inside. The polymer pellets fed through the hopper are melted and mixed in the barrel before the filament is extruded through the die. The dimension of the barrel is determined based on the dimensions of the screw and flight clearance. Therefore, the inner diameter of the barrel is the sum of the screw diameter and twice the clearance calculated above, which yields 20.04 mm. Based on this information, the 3D CAD model of the barrel is done on SOLIDWORKS 2020 as shown in Figure. 5.

The barrel must be able to withstand high temperatures and must be hard enough to resist wear caused by friction between the inner face of the barrel and the plastic flow. Considering tolerance and availability in the market, a hot- dip ¾" internal diameter galvanized steel pipe that has been dipped in a protective zinc coating meets the functional requirement of the barrel and was selected

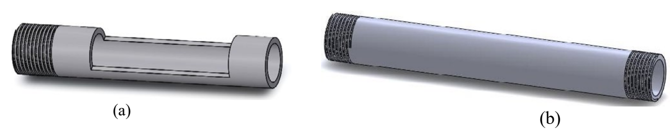


Figure 5: CAD model of barrel: (a) feeding section for hopper installation and (b) heating section

Figure 6: Manufactured barrel: (a) feeding section for hopper installation and (b) heating section

2.2.3.Hopper

The hopper holds and feeds a sufficient amount of raw material (pellets) to the screw. To reduce any conveying problems, a wedge-shaped gravity-fed hopper with a mass flow of the plastic pellets to the barrel, shown in Fig. 7 (a), is designed. The hopper can be manufactured from steel sheets or 3D printed. Manufacturing using a 3D printer helps to fit properly the hopper with its support and the barrel opening. However, printing the whole hopper consumes too much filament. The hopper was manufactured into two cross-sections and finally assembled. The bottom part is 3D printed using PLA filament to best fit its opening with the barrel opening and the upper part is manufactured from a 3mm thick MDF using a laser cutter and then assembled as shown in Fig 7 (b).

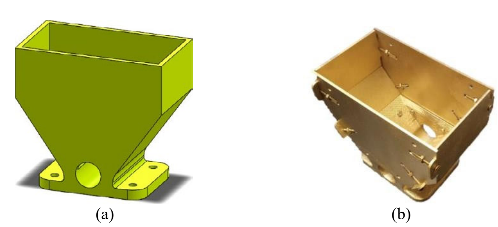
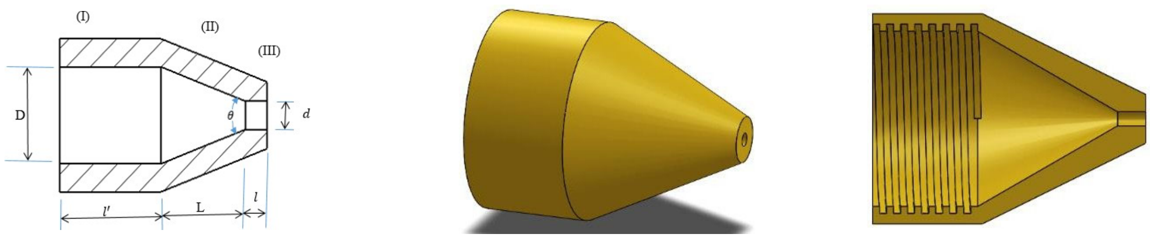


Figure 7: CAD model of the hopper (a), and its manufactured assembly (c)

2.2.4. Die

The die is used to mold the final dimension of the extrudate to the required shape and size. The die is designed based on the design of a straight cone nozzle used for FDM 3D printing hot end. It is a high-performance nozzle [26– 28] with three cross-sections: the access (I), contraction (II), and exit (III) sections as shown in Fig. 9 (a). The access section is part of the nozzle that connects to the barrel. The contraction section is used to increase the pressure of the molten polymer. The exit section is used to stabilize the flow rate of the molten polymer and gives the final size of the filament. The inlet diameter of the straight cone nozzle is equal to the core diameter of the barrel thread and is taken as 24.835mm. The exit section of the nozzle is required to extrude a 1.75mm diameter filament and it is taken as 2mm. For a 2mm outlet diameter nozzle, the contraction angle of the conical section is 60 degrees and the length of the exit section to diameter ratio (l/d) is 2mm [28]. Based on these dimensions and trigonometric relations, the CAD model of the extrusion nozzle was created using SOLIDWORKS 2020 software, as shown in Fig. 10 (b) and (c).



(a) (b) (c)

Figure 8: Cross-section of straight cone nozzle (a) and 3D model of the filament extruder machine (b) and its cross-section (c)

Brass is chosen for nozzle material due to its ability to withstand high temperatures, easy machinability, and high corrosion resistance properties. It is fabricated by performing various machining operations such as turning, facing, tapering, drilling, boring, and threading, as shown in Fig. 9 (a) and (b), according to the design parameters. Teflon tape is wrapped around the threads of the barrel and the nozzle, as shown in Fig 9 (c), to prevent extrudate leakage during extrusion.

(a) (b) (c)

Figure 9: Extrusion nozzle (a), its internal feature (b), and tightening it with barrel (c)

2.2.5. Drive System

The driving system, which consists of an extrusion motor, coupler, power supply, and thrust bearings, is used to support the screw inside the barrel and turns it at a specified speed. The extrusion motor is used to provide the power and torque to drive the screw. Plastic extrusion requires high torque to overcome the rotational resistance of the screw and provide enough force to push the plastic through the barrel, and steady speed to control the quantity of material delivered to the nozzle. The coupler is used to connect the motor shaft and the shank of the extrusion screw which results in the translation movement of the raw materials toward the heated barrel. Kickback protection is required to resist the enormous amount of pressure that builds up while the extrusion screw conveys the raw materials, which could harm the extrusion motor. The thrust bearing is used to protect the screw from backward push which occurs when the material is delivered through the barrel opening. It is fixed along the axis of rotation of the screw and is capable of withstanding a lot of thrust loads generated by the screw. A 12mm bore diameter and 32mm outer diameter axial ball thrust bearing, which can be exactly fitted with the shank of the screw, was used as shown in Fig. 10 (a).

A power supply transforms the electric current from the supply to the right current, voltage, and frequency, and then distributes it to the load. For this study, a 12V, 400W power supply shown in Figure. 10 (b) is used to power the extrusion motor, cooling fans, puller motor, spooler motor, and other electronics. It converts the 220V mains voltage from the wall outlet to 12V.

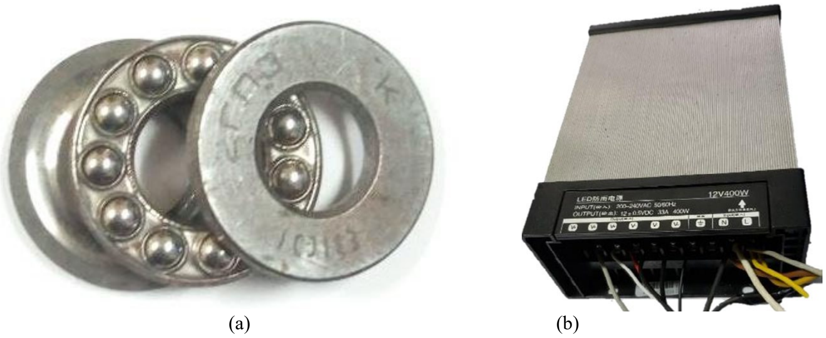


Figure 10: (a) Thrust bearing and (b) Power supply

2.2.6. Heating Element and its Control System

The heating element of the extrusion system is used to give the appropriate melting temperature of the polymer. The control system, which consists of the PID temperature controller, thermocouple, and solid-state relay, stabilizes the required temperature to melt the polymer.

1) Heating Element: The heating element is used to provide the necessary heat energy to melt the raw material. To extrude a wide variety of thermoplastics, the heater system is selected by considering the maximum melting temperature for PET polymer which is 260℃. For this study, a 500W band heater is used to melt the raw material at the appropriate temperature. For efficient viscosity of the extrudate, each zone of the screw was intended to have at least one band heater. However, only one band heater is used in this study due to budget shortage. To fit with the outside diameter of the barrel, a band heater having an inside diameter of 26mm is used as shown in Fig. 11 (a). The heater requires a voltage of 220V from a wall outlet, which can raise the temperature to 400℃. It is adjusted by a PID controller to an appropriate melting temperature of the polymer being extruded.

2) Thermocouple: To maintain the optimum condition for the plastic extrusion, the measurement of temperature is necessary. The thermocouple is an electrical device that measures temperature using the thermoelectric effect. K-type thermocouple, the most common type of thermocouple used in manufacturing and commercial applications, with an M6 tightening bolt as shown in Fig. 11 (b) was used to measure the temperature. It can measure temperatures ranging from -200°C to +1350°C.

3) PID Temperature Controller: Plastic extrusion needs a heating control system to monitor the temperature required to melt the polymer. A PID controller is a closed-loop feedback mechanism used in control systems to make a smooth change of parameters without any oscillation. It generates an error value and adjusts a control variable over time to reduce the error. It can compute the desired value of the parameter quickly and can hold the position with great accuracy. For this study, the MTD-72 Maxwell PID temperature controller, shown in Fig. 11 (c) is used to maintain a precise stable temperature. It is capable of controlling temperatures up to 400°C.

4) Solid-State Relay: A solid-state relay (SSR) is an electrical switching device that regulates the temperature of a heating element by turning it on or off when a small external voltage is supplied across the control terminals. When the temperature is insufficient, the SSR will send power to the heater, and when the temperature exceeds the required level, the SSR will switch off the current. For this study, a Maxwell MS-1DA4860 SSR shown in Fig. 11 (d), which is compatible with the PID controller, is used to regulate the temperature of the heating element. It is powered by a 220V AC supply source.

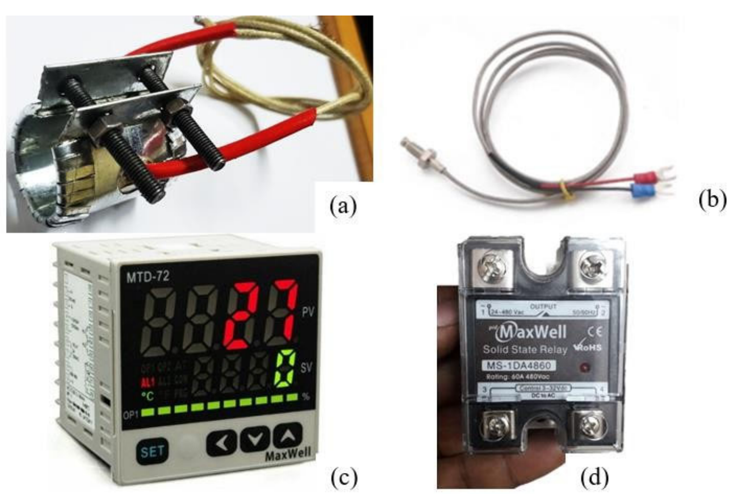


Figure 11: Heating element and its control system: (a) Band heater, (b) K-type thermocouple, (c) PID controller, and (d) Solid-state relay

2.2.7. Cooling, Pulling, and Spooling System

The extruder screw speed, cooling strategy, and puller speed are used to control the final dimensions of the filament.

1) Cooling System: To obtain high-quality smooth filaments, the molten extrudate at the nozzle outlet should be cooled and solidified using an appropriate quenching medium such as water cooling, air cooling, and others. For this study, a forced-air cooling system using two 80x80x25 mm, 12V brushless DC cooling fans were used to cool the molten extrudate at the exit section of the nozzle. The cooling fans are easily accessible, cost-effective, and are just enough for prototyping purposes to cool and solidify the HDPE extrudate at the nozzle exit. The cooling fans blow air to an angle iron that is supported by two troughs at its end. The closeness of the cooling system to the nozzle outlet is made easily adjustable.

2) Pulling System: The puller is a crucial component of the extrusion system to draw the extrudate and determine the final diameter of the filament. A faster pulling speed produces a smaller filament diameter whereas a slow pulling speed produces a larger filament diameter. For this investigation, roller pullers powered by a Nema23 stepper motor with a TB 6600 driver are used to draw the filament from the nozzle exit. The motor speed is controlled by Arduino programming to get the correct diameter.

3) Spooler: The spooler system wraps the filament around the spooler hub. It consists of a spooler hub, Nema 17 stepper motor with A4988 driver, and Arduino Uno controller for rotating the spooler hub and support fitted with radial ball bearings.

2.2.8. Construction of the Machine

The components of the filament extruder machine that were designed, modeled, and sub-assembled are finally assembled with the frame, supports, and other auxiliary components, by computer-aided design (CAD) modeling using SOLIDWORKS 2020 software as shown in Fig. 12. An angle iron of 40mmx40mmx3mm frame structure is used to support the overall mechanical and electrical components of the machine. To keep this working area safe and to a 1250mmx310mmx150mm overall frame size was found large enough, and desktop-size to handle other supporting plates for motors, auger screws, barrel, hopper, puller, spooler, electronics components, and others, The assembling of the machine on the software was made using a variety of bolts, nuts, washers, and lead screws by considering the real manufacturing and assembling of the prototype.

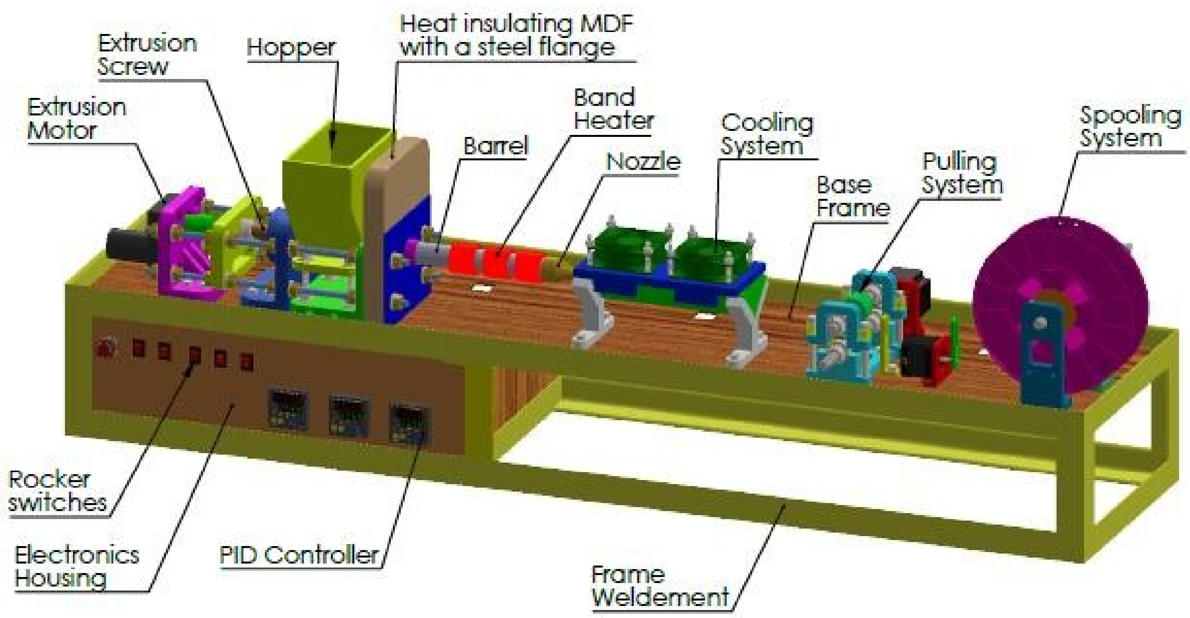


Figure 12: The 3D CAD model of the filament extruder machine

The mechanical components of the machine were manufactured using different machining operations as discussed in the preceding section. After finishing the manufacturing process, the machine was assembled using various assembly tools and equipment such as bolts, nuts, and washers. The final assembly of the machine comprises the integration of the mechanical components of the machine with electrical components, as shown in Fig. 13.

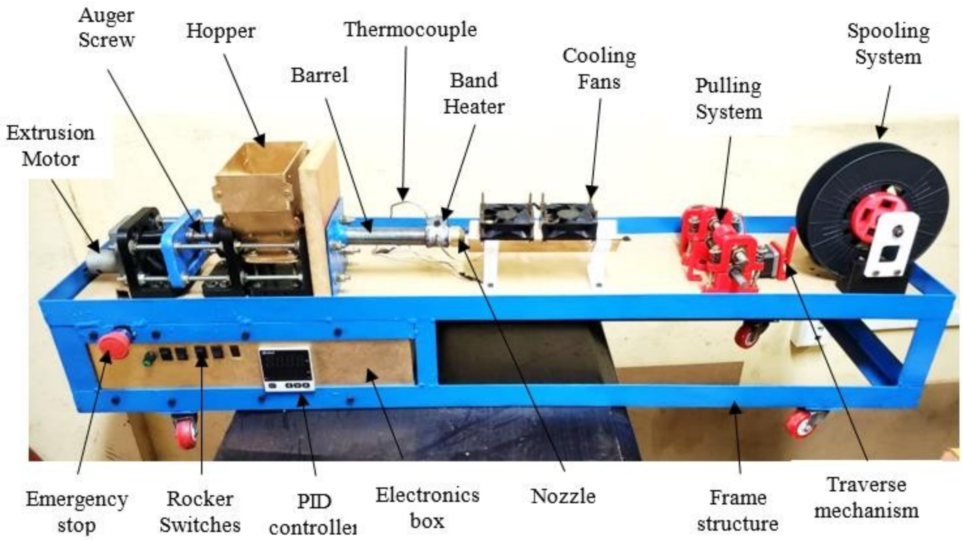


Figure 13: Assembly of the filament extruder machine.

2.3. Wiring Diagram of Electrical Components

The wiring diagram of the overall filament extruder machine is shown in Fig. 14. The entire system runs on two voltage systems: a 220V wall outlet and a 12V DC power supply outlet. To ensure machine safety, the ground is connected to the power supply ground. The heating element runs on the 220V system which runs directly to the PID

controller, band heater, and solid-state relay. It's connected directly to the power supply's 220V ports. The auger motor, puller motor, motor controllers, and cooling fans are connected to the 12V power supply port through separate wires. The entire system is switched from the wall outlet with an emergency pushbutton switch to stop power across all the machine components easily in case of an emergency.

2.4. Filament Extrusion

The working principle of the filament extrusion machine is clearly shown in a flow chart in Fig. 15. The filament extruder machine was first attached to the power source and the push button switch was turned on. The heater's temperature is then set using the PID temperature controller. The heater band begins to heat the barrel, while the K- type thermocouple begins to measure temperature and feeds it back to the PID temperature controller. The solid-state relay will turn off the heating band when the temperature exceeds the required heating value and it will turn on when the temperature drops. The extrusion motor rocker switch is turned on when the required heating value is maintained, and the extrusion auger screw begins to rotate. The raw materials are put into the hopper and conveyed to the heating section of the barrel by the rotating auger screw. The molten material is then extruded via the nozzle. The extrudate will be cooled and solidified by the cooling system. Finally, the filament will be drawn by the puller and wound around a spooler hub. In the case of an emergency, the emergency push-button switch can be turned off to stop the overall current flow in the system and protects the machine from damage.

During filament extrusion, the response variable is the diameter of the filament. The filament should have a consistent diameter throughout its length, with some manufacturing tolerance. Extrusion speed, extrusion temperature, and puller speed are the most significant extrusion process parameters. Based on the preliminary studies, an extrusion speed of 15rpm, 20rpm, and 25rpm, a melting temperature of 180℃, 200℃, and 220℃, and a puller speed of 2rpm, 5 rpm, and 8 rpm was determined. Nine different test runs were generated based on the L9 orthogonal array, as shown in Table 1, and the filament extrusion process was performed, as shown in Fig 16 (a), according to the design of experimental (DOE) that has been made.

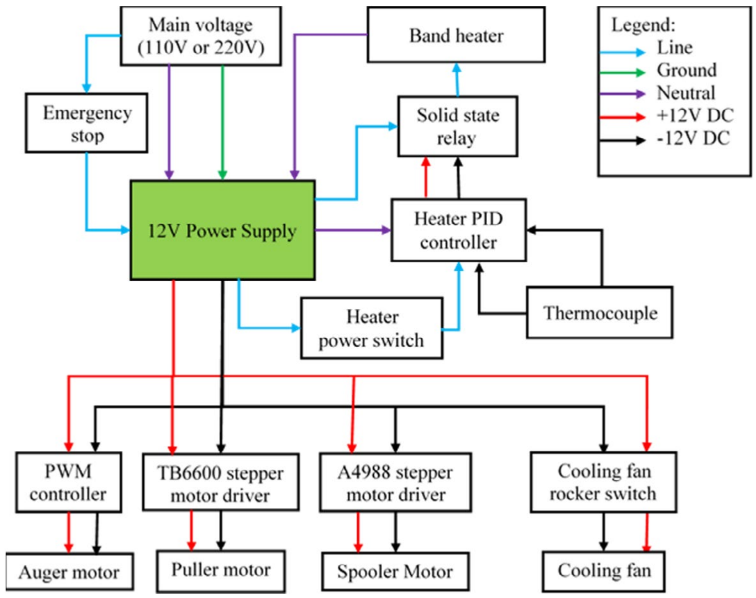


Figure14: Wiring mechanism of the electronics components

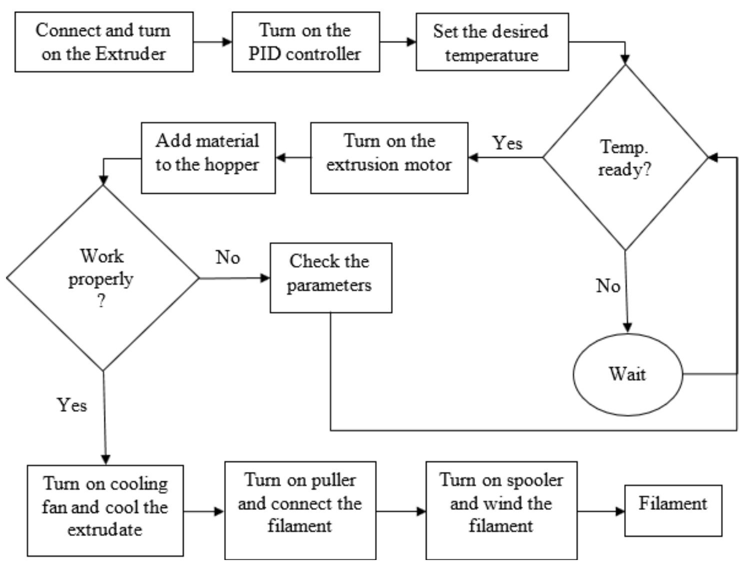
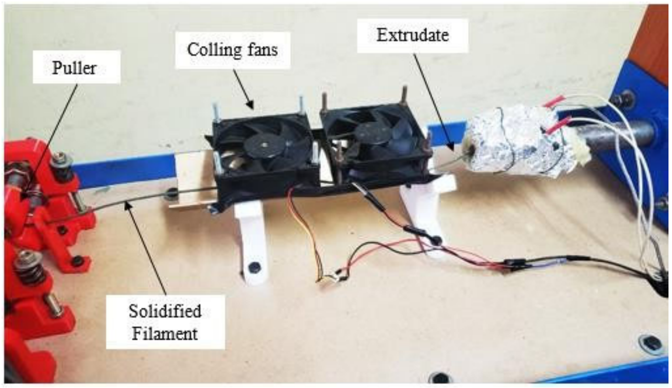


Figure. 15: Working principle of filament extruder machine

Test run	Extrusion temperature (°C)	Extrusion speed (rpm)	Pulling speed (rpm)
1	180	15	2
2	200	15	5
3	220	15	8
4	200	20	2
5	220	20	5
6	180	20	8
7	220	25	2
8	180	25	5
9	200	25	8

Table 1: Design of experimental (DOE) of recycled HDPE filament Extrusion process parameters



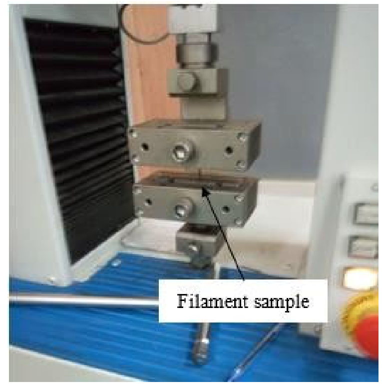


Figure. 16: Recycled HDPE filament extrusion (a), and its tensile testing using a universal tensile testing machine (b)

2.5. Filament Characterization

The recycled HDPE 3D printing filament was investigated for its physical, mechanical, thermal, and chemical properties by conducting various tests such as Tensile test, Thermogravimetric analysis, and Fourier Transform Infrared Spectroscopy, water absorption test. The result obtained was analyzed and validated by comparing it with its virgin counterpart to determine the potential of utilizing it for 3D printing filament.

1) Filament roundness and diameter consistency: A digital micrometer with a 0.01 tolerance was used to measure the diameter of recycled HDPE filaments. A 2.5m length of HDPE filament was used as a sample, and its diameter was measured vertically and horizontally at a length of 100mm twice per point of measurement. The average diameter of the filament was calculated and compared with standard 3D filament size.

2) Tensile Testing: The tensile testing of the filaments was conducted using MesdanLab Strength Tester, with a maximum load of 5kN and load speed of 200mm/min, according to ASTM D638-1 standard. Five 100mm long filament samples with a gauge length of 25mm were prepared and the test was conducted as shown in Fig. 16 (b). The result was validated by comparing the strength of recycled HDPE filament with its virgin counterpart based on the literature review.

3) Fourier Transform Infrared (FTIR) Spectroscopy: The structure (functional group) of the recycled HDPE filament was determined using Fourier transform infrared (FTIR) spectroscopy (JASCO FT/IR-6600 FTIR spectrometer). A thin slice of filament sample was combined with potassium bromide (KBr) and placed in the test section. The spectral resolution was scanned in the range of 4000–400 cm-1 with a resolution of 4 cm–1 at a scanning speed of 2mm/s.

4) Thermogravimetric Analysis (TGA): The thermal stability of the filament was analyzed by using Thermogravimetric analysis. A filament weighing 8mg was placed in a sample compartment of the Beijing Henven HCT-1 thermal balance thermogravimetric analyzer. Thermogravimetric analysis and heated from room temperature to 800°C at a heating rate of 20°C/min. The percentage weight loss evolved during TGA was analyzed and the onset degradation temperature as well as the final degradation temperature was determined and compared with the virgin counterpart based on a preliminary study.

5) Water Absorption Test: Five 50mm-long test specimens were examined for a water absorption test according to the ASTM D570 standard. The weight of the samples was measured using a digital mass balance after conditioning it in an oven. The conditioned samples were then immersed in distilled water for 24 hours at room temperature. After wiping away all moisture content with a dry cloth, the samples were weighed using a digital mass balance and returned to the water. Weight was measured and recorded every 24 hours for six days and the total amount of water absorbed was calculated when substantially saturated. To be as precise as possible, the average values of the test results were used.

3. Result and Discussion

3.1. Fabrication of Recycled HDPE Filament

The production of consistent filaments is a prerequisite for achieving a uniform output from an FDM printer since the printer alone regulates the amount of polymer depending on the speed of the feeder that delivers the filament into the extrusion die. The recycled HDPE filament was produced on the custom-built single-screw extruder equipped with a die having a diameter of 2.00 mm, an air-cooling, a puller, and a spooler (winding) system. Several preliminary tests were conducted. Different filament sizes and qualities were observed and the best combination was selected for characterization and validation test runs. The outcomes of the various HDPE filament extrusion test runs carried out at various extrusion process parameters and their qualitative description are provided in Table 2. The best quality recycled HDPE filament, as shown in Fig. 17 (a) and (b), was produced at test run 5 with extrusion process parameters of a 20rpm screw speed, a 220°C melting temperature, and a 5rpm pulling speed compared to other test runs. It has a smooth surface, round shape, extrusion consistency, and better filament quality compared to other test runs. The filament produced also wrapped easily around a spooler hub without breaking and cracking as shown in Fig. 17 (c). This shows that recycled HDPE filament has excellent toughness and ductility. Further characterizations were conducted on it in the succeeding section.

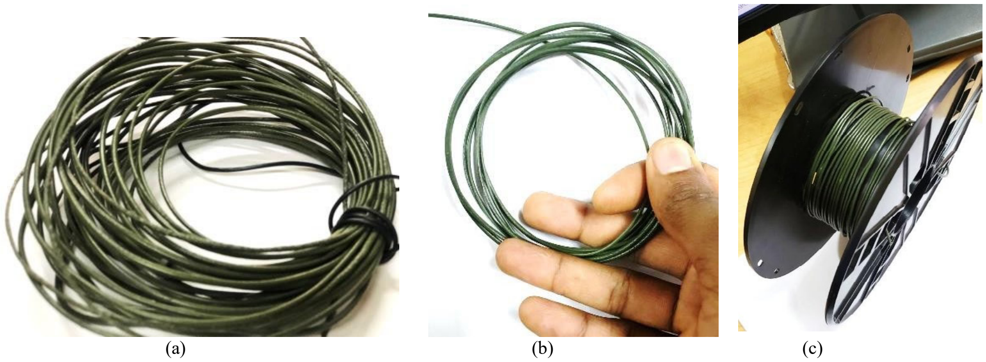


Figure 17: Extrusion of recycled HDPE filament (a) and products produced at test run 5 (b)

Test run	Extrusion Parameter			Average filament diameter (mm)	Qualitative description of the result
	Ext. Temp. (℃)	Ext. speed (rpm)	Pulling speed (rpm)		
1	180	15	2	1.93 ±0.04	Inconsistent, rough surface, brittle, and too thick filament
2	200	15	5	1.84±0.02	Rough and inconsistent filament, better polymer melting than a test run 1.
3	220	15	8	1.58±0.22	Polymer pellets fully melt smooth surfaces, insufficient pressure of molten plastic, too thin filament.
4	200	20	2	1.78±0.02	Good viscosity of extrudate, surface roughness, brittle filament, and too thick filament
5	220	20	5	1.75±0.01	Polymer pellets fully melt, have good extrudate viscosity, smooth, round shape, extrusion consistency, and better filament quality compared to others.
6	180	20	8	1.65±0.22	Polymers pellets do not fully melt, have high surface roughness, and high diameter
7	220	25	2	1.79±0.2	Polymers pellets fully melt, have high extrudate pressure, round shape, and consistent filament, Too thick filament
8	180	25	5	1.86±0.04	Good extrudate pressure, but pellets do not fully melt, rough surface, and high diameter
9	200	25	8	1.68±0.02	Good extrudate pressure, good polymer viscosity, Good surface roundness, and diameter consistency, but slightly a thin filament

Table 2. Results of the different test runs of the recycled HDPE filament extrusion

3.2. Filament Characterization

3.2.1. Filament Diameter Consistency

Smooth and round recycled HDPE filament, as shown in Fig. 17, was produced at test run 5. The diameter of the filament was measured over a 2.5m length sample at 26 consecutive measurement points using a digital caliper as shown in Fig. 18. The variation of the recycled HDPE filament diameter over the span length was obtained negligible with an average diameter of 1.75mm ±0.001 which lies within the tolerance of the commercial filament (1.75±0.05).

3.2.2. Tensile Testing

To evaluate the mechanical strength of the recycled HDPE filament, tensile tests were performed on five samples of recycled HDPE filaments, and its stress-strain curve is shown in Fig 19. The tensile testing result such as ultimate tensile stress (MPa), maximum elongation, and tensile strength at failure for the recycled HDPE and the virgin HSDPE filament are summarized in Table 3. The ultimate tensile strength of the recycled HDPE filament was found 19.08 MPa. The result reveals that the tensile strength of the recycled HDPE filament is nearly equivalent to that of its virgin counterpart, based on a literature survey [29], with the virgin HDPE filament's tensile strength being slightly higher (5.84%) than that of the recycled HDPE filament. However, there is no significant variation and the result shows a comparable strength of the recycled HDPE filament with its virgin counterpart making it suitable for use as source material for 3D printing.

Figure 18: Measuring of the produced recycled HDPE filament diameter at different points

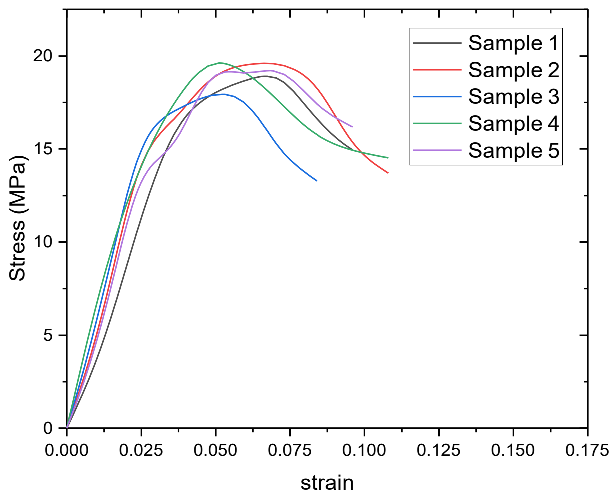


Figure 19: Stress vs strain graph of the five samples of recycled HDPE filament

Mechanical properties	Recycled HDPE Filament	Virgin HDPE filament [29]	Injection molded HDPE specimen [29]
Ultimate tensile strength (MPa)	19.02±0.35	20.2±0.7	28
Yield stress (MPa)	16.59±1.35	14.0±2.8	-
Young's Modulus (MPa)	605±120.8	904±250	830

Table 3: Mechanical properties of recycled HDPE filament

3.2.3. Fourier Transform Infrared Spectroscopy (FTIR):

The recycled HDPE filament has peak characteristics of a strong band at 1472.39 cm-1, 2916.81 cm-1, and 717.38 cm-1, which reflect methyl C–H symmetrical bending, –CH2 asymmetrical stretching, and long-chain methyl rocking vibrations, respectively which reveals that recycled HDPE filament has the same functional groups as the virgin HDPE polymer. The recycled HDPE filament, as shown in Fig 20, possesses ranges of characteristic peaks, which are similar to the virgin HDPE polymer's range of spectra in the literature [30–32]. However, the FTIR spectra of the recycled HDPE filament show extra tiny peaks at 879–1300 cm-1. These peaks may be due to the presence of some pollutants, such as the ether group (C– O), in post-consumer HDPE plastic granules that were not extensively cleaned during the preparation of the raw material.

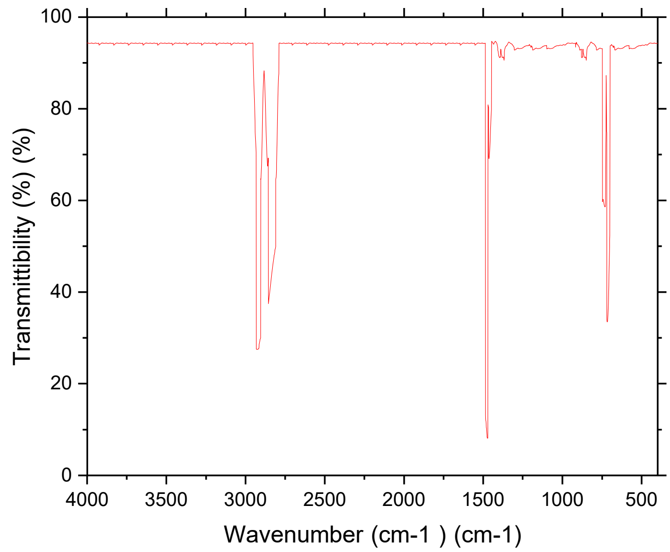


Figure 20: FTIR spectrum of produced recycled HDPE filament.

3.2.4. Thermogravimetric Analysis (TGA)

TGA is a crucial evaluation to ascertain the thermal stability of recycled HDPE filament because the recycling processes might degrade HDPE and further affect its long-term properties. The recycled HDPE filament showed a one-step (single peak) degradation with an initial (onset) degradation temperature of 430℃ and the full degradation temperature of 520℃ with a percentage weight loss of around 90% as shown in Fig. 21. Thermal stability of the recycled HDPE filament was compared with its virgin counterpart based on literature reviews[33–35]. The recycled HDPE filament shows comparable thermal stability compared to its virgin counterpart.

3.2.5. Water Absorption Test

The percentage weight increase of the samples across the six days is shown in Fig 22. After six days of immersion in distilled water at room temperature, the recycled HDPE filament shows almost negligible water absorption, with a weight gain of 0.12% (0.12mg) compared to the conditioned sample. The result reveals that the recycled HDPE filament has a high-water rejection capability. The negligible percent weight increase results from some moisture at the surface. It also shows that the produced filament doesn't have porosity at the surface due to the negligible percent weight increase. If there were porosities in the filament, it would absorb the water through it and its weight might increase.

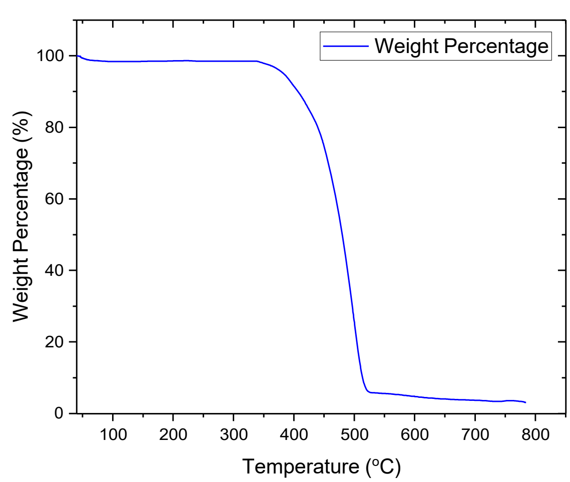


Figure 21: TGA result of recycled HDPE filament

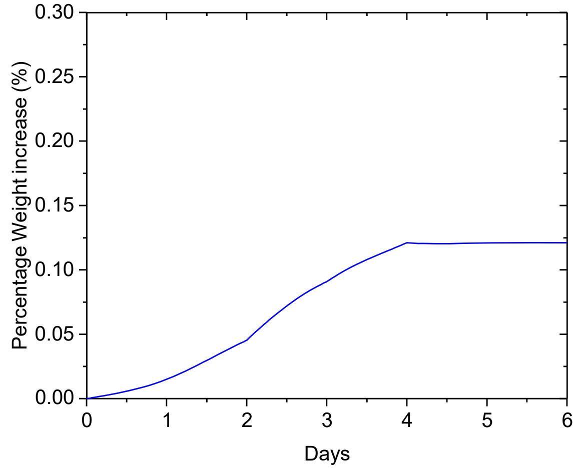


Figure 22: Percentage weight increase of recycled HDPE filament

3.3. Discussion on challenges and future outlooks for 3D printing with HDPE

Utilizing post-consumer recycled HDPE for 3D printing filaments will create a new use for discarded wastes. However, HDPE poses a variety of difficulties for 3D printing, including warpage, shrinkage, and poor adhesion to build plates. When the temperature drops, HDPE material often shrinks, curls, or warps significantly. The bottom layers, which have a lower temperature, will probably shrink as the item is built up layer by layer, leading to distorted shapes. Furthermore, HDPE does not attach to anything other than heated HDPE, which presents an additional issue when printing with it [23]. Due to these constraints, HDPE is rarely employed in 3D printing applications. Nonetheless, Table 4 summarizes a variety of feasible suggested techniques for 3D printing of HDPE. On a large-format FDM printer modified from a plasma cutter, the Washington Open Object Fabricators (WOOF) team produced a functional boat from post-consumer HDPE milk bottles. To accomplish a mechanical bond, the team employed a pegboard build plate with countersunk holes and a fused HDPE surface used as a printing substrate. To prevent warping, a heater was attached to the extruder to soften the preceding layer, and a sacrificial flange was mechanically screwed to the build plate. The prior layers were melted for adhesion by extruder heaters, and a specialized print substrate created a mechanical bond. When coupled with the bolted flange, this approach allows for the printing of a large boat [36]. By varying 3D printing parameters and using poly(styrene-blockethene-co-butene-block-styrene) (SEBS) copolymer building plate heated at 60°C, Schirmeister et al. [37] offered good adhesion throughout the printing process. A range of materials such as stick glue, HDPE plastic bag, and clamp can be utilized to improve adhesion with the print plate [38, 39]. To increase the potential and market competitiveness of recycled filaments, further investigation will be required to optimize the filament extrusion and 3D printing process parameters, improve the mechanical properties, and overall development methods for both the recycled HDPE filament and 3D printed products.

Material	Proposed solutions	Result	Reference
Recycled HDPE from milk jugs	Print quickly using a sacrificial flange that is mechanically screwed to the build plate. Countersunk holes were employed in the pegboard print substrate.	Heaters on the print head melted the layers beneath for adhesion, and the print substrate produced a mechanical bond.	[36]
Virgin HDPE	Used SEBS block copolymer plate heated at 60°C	SEBS offered good adhesion throughout the printing process.	[37]
Recycled HDPE mixed with LLDPE and Millad 3988i	Printing on a glass plate covered with a thin layer of PVA- based glue	Additives and print strategy reduced warpage and enabled the printing of variously shaped items.	[38]
HDPE - Core PC/ABS - Shell	PC/ABS core bonded by a heated print substrate and covered with a thin layer of PVA-based glue	PC/ABS core bonded by a heated print substrate and covered with a thin layer of PVA-based glue	[39]
Virgin HDPE reinforced with TMP fibers	Used standard FDM printer without heated print substrate.	Lower MFI HDPE grades showed better printability than higher grades.	[40]

Table 4: Proposed solutions to the warping and adhesion issues of HDPE filament for 3D printing

4. Conclusion and future outlooks

The environmental pollution caused by plastic waste and the high demand for polymer feedstock materials for FDM 3D printing can be mitigated by manufacturing low-cost, user, and environmentally friendly recycled HDPE filament. In this study, a filament extruder machine was built and used to produce a smooth and round-shaped recycled HDPE filament. A 1.75±0.01mm diameter recycled HDPE filament was produced at a heating temperature of 220℃, screw speed of 20rpm, and pulling speed of 5rpm using a 2mm die outlet. The size of the filament lies within the range of the standard filament size of 1.75(±0.05) mm. Furthermore, physical, mechanical, chemical, and thermal characterization of the recycled HDPE filament was conducted and validation was done by comparing it with its virgin counterpart. The results of the tensile tests demonstrate that the ultimate tensile strength of the manufactured filament was 19.02±0.35 MPa, with the virgin HDPE filament's tensile strength being slightly higher (5.84%) than that of the recycled HDPE filament. The result reveals that the recycled HDPE filament has good strength that is comparable to its virgin counterpart. The FTIR spectra of the recycled HDPE filament were also obtained equivalent to the spectrum of virgin HDPE material with small variations indicating some impurities. Thermogravimetric analysis (TGA) showed that the recycled HDPE filament has significant thermal stability with an onset degradation temperature of 430℃ and a full degradation temperature of 520℃ which is comparable to that of pure HDPE polymer. The recycled HDPE filament was also checked for water absorption and the result reveals that it has high water rejection capabilities with a rise of 0.12% by weight after immersing it for six days in distilled water.

To increase the potential and market competitiveness of recycled filaments, further investigation will be required to optimize the filament extrusion and 3D printing process parameters, and improve the mechanical properties, and overall development methods for both the recycled HDPE filament and 3D printed products. Further study is also required to extrude the recycled HDPE by blending it with additives to increase its strength and make it useful for functional products.

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