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PET bottle recycling and filament production for 3D printing: design and development of a sustainable extrusion system

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***Abstract*— The widespread use of plastics, particularly polyethylene terephthalate (PET), has created both economic opportunities and severe environmental challenges. As plastic consumption continues to rise globally, innovative recycling and reuse strategies become essential to mitigate the ecological burden of plastic waste. One promising approach is the repurposing of PET bottles into usable 3D printing filament, thereby transforming waste into value-added products. This paper presents the design and development of a PET recycling and filament manufacturing system for 3D printers. The work integrates knowledge of polymer chemistry, thermomechanical design, and additive manufacturing, with an emphasis on environmental awareness and sustainability. The system is designed to cut, shred, and extrude PET waste into filament suitable for Fused Deposition Modeling (FDM) printers. Experimental results demonstrate the feasibility of producing consistent filament diameters with acceptable mechanical performance, though several material-related challenges remain. This study contributes to circular economy practices by promoting localized recycling, enabling decentralized filament production, and reducing both environmental impact and raw material costs.**

***Keywords*— PET, plastics, 3D print, environment**

I. INTRODUCTION

Since their invention in the 1860s, plastics have revolutionized the manufacturing industry. In the mid-19th century, scientists were searching for a low-cost synthetic compound that could replace natural materials, which at the time were both expensive and difficult to produce. Over the decades, increasingly complex plastics were developed, and today these materials are integrated into nearly every aspect of modern life, from clothing and furniture to the automotive industry. In fact, contemporary society is fundamentally built upon plastics. However, this advancement comes at a cost: plastics are highly durable materials, making them extremely difficult to recycle without causing environmental harm [1].

Natural polymers have long existed as part of the environment. For instance, rubber, a naturally occurring polymer, was already in use during the 11th century by the Maya civilization for making balls used in ritual games. The basis of all plastics is the macromolecule, a structure composed of repeating identical units. The starting material is the monomer, which can be considered the fundamental molecular unit representing the full chemical structure. Polymers are formed by the aggregation of such repeating macromolecules. In scientific terminology, the word "polymer" typically refers to both natural and synthetic materials, whereas "plastic" is more commonly used when referring specifically to artificially produced polymers [2]. Figure 1 shows the chemical composition of PET [3].

Fig. 1. Chemical structure of PET [4]

One of the most widely used synthetic polymers is PET, the abbreviation of polyethylene terephthalate, a name derived from its chemical composition. Its molecular formula is $C_{10}H_8O_4$, consisting of 10 carbon atoms, 8 hydrogen atoms, and 4 oxygen atoms. PET is synthesized through a polycondensation process and belongs to the category of linear thermoplastic polyesters. Within the group of saturated thermoplastic polymers, it is classified as having a crystalline structure. While semi crystalline or crystalline plastics are generally opaque, PET can exhibit transparency due to the fact that its crystal lattice is smaller than the wavelength of visible light. Figure 2 is an example for polymer usage.

Fig. 2. Polymer particle toys [5]

PET loses mechanical strength at approximately 70–75°C, referred to as the crystallization temperature, and melts at around 210–270°C. Owing to these properties, it is easily moldable: when cooled rapidly, it solidifies into an amorphous structure, while slow cooling allows it to form an ordered crystalline arrangement. In its solid state, PET demonstrates high impact resistance and strong chemical stability, making it suitable for storing oils, acids, alkalis, and hydrocarbons. For this reason, PET has become a key industrial material, widely employed in the manufacturing of containers and bottles. Additionally, because it is largely resistant to microorganisms and various forms of radiation, it is particularly suitable for food packaging applications.

The production process of PET bottles involves first creating a preform resembling the final product, followed by expansion through injection blow molding. In this process, the molten polymer is injected into a mold, where it assumes the required shape. Once cooled, the resulting product is immediately ready for practical use. PET is also highly compatible with 3D printing technologies, where it is applied in the production of models and prototypes. Figure 3 introduces the worldwide PET recycling and production [6].

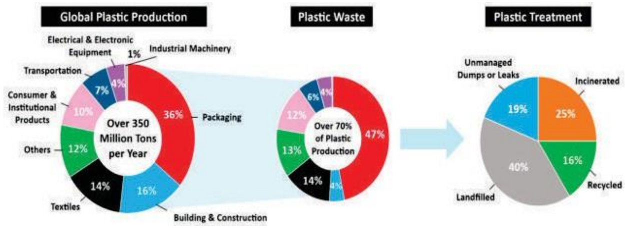

Fig. 3. Global plastic production and recycling [6]

Nevertheless, despite its many advantageous properties, PET poses a significant environmental challenge. Due to its high durability and resistance to degradation, it persists in nature for extended periods. PET waste can remain in the environment for up to half a century, with consequences that extend across multiple future generations. Figure 4 demonstrates the possible degradation of PET material.

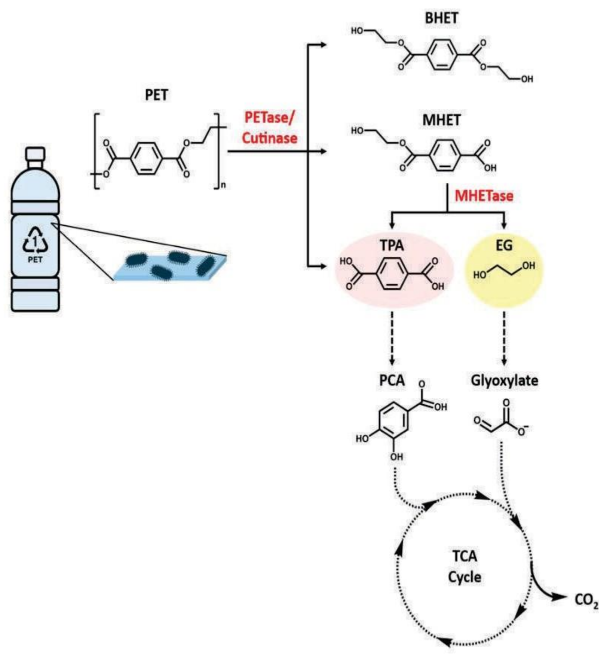

Fig. 4. Microbial degradation of PET [6]

This paper addresses both environmental and technological challenges by proposing a system for transforming PET bottles into usable filament for 3D printers. By bridging polymer recycling with additive manufacturing, this approach has the potential to support local circular economies, reduce waste, and provide affordable materials for innovation.

II. MATERIALS AND METHODS

A. 3D printing technology and materials

3D printing is an additive manufacturing technology, meaning that products are fabricated through the successive addition of material. Several different 3D printing technologies exist, including stereo-lithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM). Among these, FDM is the most widely used method. This technique employs thermoplastic polymers or other heat-meltable materials to build objects layer by layer. The thermoplastic filaments are supplied from a spool, which is placed in the printer's material feeder. The build platform, on which the model is formed, is typically heated in order to prevent deformation during the process.

The extruder precisely regulates the flow of the filament, which is heated by the hot end to a defined temperature. Subsequently, the nozzle deposits material in successive layers, gradually constructing the model. The advantages of FDM technology include its relatively low cost, the wide variety of filament types and colors available, and the ease of maintenance and operation of FDM printers. However, as with many other technologies, there are disadvantages as well. The most noticeable drawbacks appear on the printed objects themselves: visible layer lines and, in general, lower dimensional accuracy compared to other 3D printing methods.

3D printing therefore represents one of the most revolutionary advances in modern manufacturing. It enables the precise fabrication of products that would be impossible—or at least extremely difficult—to produce using conventional manufacturing techniques. For this reason, additive manufacturing is particularly suitable for prototyping as well as for the production of specialized assemblies [7].

The three most commonly utilized materials in additive manufacturing are PLA, ABS, and PET, with PLA being the most prevalent. PLA is widely adopted due to its excellent printability and because, in general, the final products meet end-user requirements when used as low-stress structural components or simple decorative objects. ABS, by contrast, exhibits higher mechanical strength and greater resistance to both physical and chemical effects than PLA; however, its vapors and emissions may pose health risks during processing. PET is more challenging to handle in printing, while its glycol-modified variant, PETG, readily absorbs moisture from the atmosphere. Nevertheless, both PET and PETG demonstrate superior toughness and durability compared to PLA and ABS.

An older, less accurate 3D printer can be repurposed to recycle discarded PET bottles into PET-based filament, thereby meeting both environmental and economic considerations. The PET bottles must first be heated to achieve a uniform surface, and their bases must be removed, as these cannot be processed by the machine. The bottle is then mounted onto a shaft, with its cut base placed into the machine's cutting section, which performs the slicing operation continuously (this stage is not automated) [8][9][10].

The resulting plastic strip is fed through the 3D printer's extruder, which has been preheated via the printer's software. During heating, the extruder head compresses the plastic strip into a tubular shape, thereby forming the filament strand. The strand is manually guided to the spool, where it is secured before the motor is switched to automatic winding mode. At the end of the process, the material collected on the spool is ready for use as recycled filament. The embedded systems regulate the whole faultless process [11][12].

B. Filament production

The filament production device converted from a Creality Ender 3 printer was designed to contribute to a cleaner future while simultaneously providing practical benefits to its user. Using a set of bearings, the machine gradually slices a PET bottle—mounted onto a long threaded rod—into a continuous strip. This strip is then processed by the Ender 3 heating head, which reshapes it into a circular cross-section. The resulting filament is collected on a spool mounted on the large gear shaft located on the opposite side of the machine, after being fixed in place. From this point onward, the process becomes automated. However, once the system reaches the narrower neck region of the bottle, the machine must be stopped, as it is unable to handle excessively tapered feedstock [13].

Structurally, the device consists primarily of 3D-printed plastic components, including many parts and coverings, in addition to original 3D printer elements such as metal frames, wiring, circuitry, a motherboard, and functional units like the heating system and the custom-designed cutting mechanism, which is adapted from a ball bearing assembly. Because the raw material consists of discarded PET bottles, it must be thoroughly cleaned before use. Moreover, a thermal treatment (e.g., with a hot air blower) is required to smooth the surface of the bottles. This ensures that the cutting device can operate effectively and without obstruction. As the PET strip passes through the heating nozzle, it adopts the shape of the extruder tip. Instead of forming a solid circular filament, it takes on a hollow, ring-shaped cross-section. This output is then fixed to the spool, enabling the automated winding process to continue until the material is depleted [14].

During filament collection, special attention must be given to the mechanical properties of PET. As a tough and highly durable material, PET stores energy when wound onto the spool. Once tension is released, it behaves similarly to a compressed spring suddenly released, which requires careful handling during subsequent processing. After spooling, however, the filament is ready for reuse and can be employed in 3D printing applications [15].

III. RESULTS

A. The process and programming

The main stages of filament production are as follows: preparation of the raw material, fixation of the raw material, cutting of the raw material, melting and extrusion of the raw material through the heating head, shaping of the raw material into the final product, winding of the finished product onto the reel, and automation of the process via the Ender-3 controller. For stabilizing the PET bottle, the bottle must be supported from at least three directions using a stand-based support system. Since a screw runs through the interior of the bottle, it is logical to utilize this feature to secure its position. However, because the screw used as the fixing column does not fully match the diameter of the bottle neck, the bottle may still "wobble" at this point during automated operation.

The structural cutting of the raw material is performed by two opposing ball bearings with sharpened edges. These bearings must have sufficient clearance and minimal friction so that the rotation of one induces the rotation of the other without obstruction. The spools were actuated using a LEGO Mindstorms EV3 robot. Figure 5 shows the structure of the cutting device.

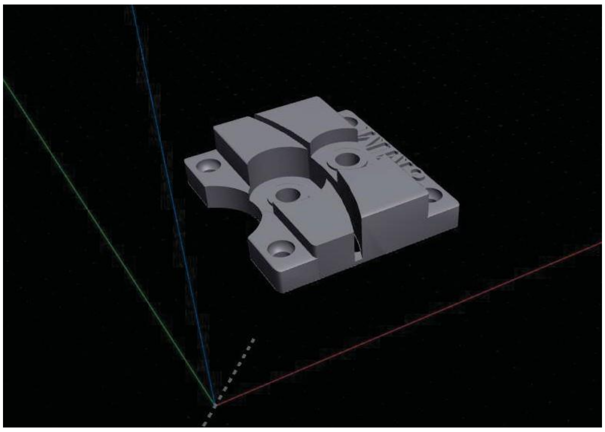

Fig. 5. Rolling bearing housing of the cutting device

Both the feed spool and the take-up spool, driven by the LEGO motors, must be controlled simultaneously to ensure the material passes through the extruder at the correct speed. In selecting the material for the spools and their holders, load capacity and low-friction properties are critical, since a motor is responsible for their drive, and the reels must rotate smoothly. These requirements are fulfilled by the plastic used in the recycling apparatus. In terms of positioning, the spools must be located in the same plane as the cutting mechanism, because the subsequent stage of the process involves a guiding element—a type of "gate" that aligns the plastic filament favorably for the heating head.

The driving motor is positioned next to the reel holder. As the motor shaft directly drives the spool, the motor must be suspended ("in the air") and fixed in place. This is achieved by aligning the central axis of the motor gear wheel with the cross-shaped axis of the feed spool. The motor need not be rigidly fixed to the machine frame; however, if operational forces require, the motor housing can be supported with vertical structural elements integrated into its mounting sockets. Figure 6 shows the recycling machine.

Fig. 6. The filament production process from PET bottle

In addition, a second motor must be mounted for the collection spool. Unlike the feed spool, this axis is not directly driven by the motor, but instead through a system of gear reductions, with the motor secured to the frame. The principle of operation is thus analogous to the feed spool mechanism. To determine motor speeds, the filament feed rate through the extruder must be known. This parameter is available from the G-code of the 3D printer that serves as the basis for the recycling machine. The specified feed rate is F300, i.e., 300 mm/min. With a reel diameter of 5.2 mm, the corresponding spool rotation speed is calculated to be 1.08853 revolutions per minute (r/min). Figure 7 describes the LEGO motor programming.

```
#include <stdio.h>
#include "ev3.h"
#include "ev3_port.h"
#include "ev3_dc.h"

int main( void )
{
        char s[ 256 ], name_port[ 16 ];
        int i;
        uint8_t sn1, sn2, sn_port;
        uint8_t port1 = OUTPUT_B; // Port for the first motor
        uint8_t port2 = OUTPUT_C; // Port for the second motor
        bool running = true;        // Flag to indicate whether motors should continue running

        if ( ev3_init() < 1 ) return ( 1 );

        ev3_port_init();

        // Initialize first motor
        sn_port = ev3_search_port( port1, EXT_PORT__NONE_ );
        set_port_mode_inx( sn_port, OUTPUT_DC_MOTOR );
        ev3_dc_init();

        // Initialize second motor
        sn_port = ev3_search_port( port2, EXT_PORT__NONE_ );
        set_port_mode_inx( sn_port, OUTPUT_DC_MOTOR );

        // Find first motor
        if ( ev3_search_dc_plugged_in( port1, EXT_PORT__NONE_, &sn1, 0 )) {
                set_dc_duty_cycle_sp( sn1, 1 ); //Setting duty cycle to 1%
                set_dc_ramp_up_sp( sn1, 2000 );
                set_dc_stop_action_inx( sn1, DC_COAST );
                set_dc_command_inx( sn1, DC_RUN_FOREVER );
        } else {
                //First DC motor is NOT found
        }

        // Find second motor
        if ( ev3_search_dc_plugged_in( port2, EXT_PORT__NONE_, &sn2, 0 )) {
                set_dc_duty_cycle_sp( sn2, 17 ); //Setting duty cycle to 17%
                set_dc_ramp_up_sp( sn2, 2000 );
                set_dc_stop_action_inx( sn2, DC_COAST );
                set_dc_command_inx( sn2, DC_RUN_FOREVER );
        } else {
                //Second DC motor is NOT found
        }

        // Run motors until stopped
        while (running) {
                // If a button is pressed, stop the motors
                if (brick_button_pressed(BUTTON_ID_ENTER)) {
                        running = false; // Set the flag to false to exit the loop
                }

                // Sleep for a short interval before checking again
                Sleep(100); // Sleep for 100 milliseconds
        }


        // Stop first motor
        if ( ev3_search_dc_plugged_in( port1, EXT_PORT__NONE_, &sn1, 0 )) {
                set_dc_command_inx( sn1, DC_STOP );
        }

        // Stop second motor
        if ( ev3_search_dc_plugged_in( port2, EXT_PORT__NONE_, &sn2, 0 )) {
                set_dc_command_inx( sn2, DC_STOP );
        }

        // Reset port modes
        set_port_mode_inx( sn_port, OUTPUT_AUTO );

        // Uninitialize the ev3dev-c library
        ev3_uninit();

        return ( 0 );
}
```

Fig. 7. LEGO Mindstorms EV3 robot programme

The larger LEGO Mindstorms EV3 motor is capable of operating at 160–170 r/min. Therefore, a reduction must be applied to the feed spool drive. Since 1% of the nominal motor speed approximates the desired value, a theoretical reduction of 34.5% would be required. However, such a reduction is not feasible with the EV3 motor and software. Moreover, the effect of this discrepancy on the heating process has not been verified; thus, for simplicity, a 1% operating value was assumed in calculations. The second (take-up) spool is directly connected to the largest gear of the assembly. This gear has 120 teeth and engages a 12-tooth gear, which in turn drives a 30-tooth gear connected to another 12-tooth gear.

Consequently, when the first gear rotates once, the second rotates ten times, and the third twenty-five times. From this ratio, the motor speed required is calculated to be 27.213 r/min. The theoretical maximum speed of the EV3 motor is approximately 165 r/min. From this, the necessary reduction ratio for proper synchronization with the extruder is computed as 16.4929%. Since the EV3 software cannot process fractional percentages, this value was rounded to 17% in accordance with rounding conventions, and applied to the control of the take-up spool motor.

B. Financial aspects

Total cost of energy consumption and filament for in-house 3D printing is about 34,000 HUF. Printing and delivery by a company is about 90,000 HUF. Since the cost of electricity is practically negligible, the overall expenses are primarily determined by the amount of raw material used, calculated on the basis of base prices without considering discounts. The material cost was estimated for 1.5 kg of ABS filament, commonly used in FDM printers, by multiplying the total mass by its unit price per gram. From this comparison, it can be concluded that in-house production remains significantly more cost-effective; however, the final expenses depend heavily on the source and method of acquiring raw materials for printing.

The calculation was carried out as follows: the total weight of the products was measured at 1425 g, which roughly corresponds to two larger spools of filament, based on prior estimates. It should be noted that some components would ideally require a denser construction material. Furthermore, as emphasized in the previously mentioned video, certain parts could be omitted entirely from production. As a compromise, the total mass of the components was taken as the basis for calculation, without further optimization of the design.

The printing process itself requires approximately 160 hours under standard conditions, but depending on the specific printer, this duration may reach 170 hours. Consequently, a consensus-based average of 168 hours was adopted for the calculations, as it allows for easier numerical processing and visualization. The Ender-3 printer consumes approximately 1.5 kWh over a 12-hour period, which translates to 0.125 kWh per hour. Over 168 hours, this results in an electricity consumption of 21 kWh. More effective energy supply can be arranged by using reliable off-grid systems [16].

IV. CONCLUSIONS

Considering that 3D printing itself is still a relatively new technology, the range of accessories and auxiliary tools associated with it is not particularly extensive. In the context of filament recycling, we mostly encounter designs and machines that aim to reuse already manufactured work pieces or defective prints; in other words, they continue to process the same materials with which they have already been working.

However, the recycling of PET bottles within the field of 3D printing is an area pursued by far fewer researchers or hobbyists. Sources in Hungarian on this topic are scarce and often difficult to find, while foreign-language sources generally refer to a single design and device — The Recreator 3D — which is a modification built upon the Ender 3 3D printer. Consequently, my subsequent work was also based on this system.

Following the introduction of The Recreator 3D, the construction costs of the device were examined with an initial hypothesis, finding that these costs remained largely unchanged. The primary variable influencing overall expenses is therefore the individual builder and their level of expertise.

Designing a cap mechanism that applies downward pressure on the feedstock material while keeping it in position was successful, also exploring the possibility of enclosing the raw material within a quasi-frame. Through the study of 3D models and program code, and by mathematically verifying theoretical implementations a new drive mechanism for the material collection and feed spools of the device using the large motors from the Lego Mindstorms EV3 system were developed.

In conclusion, the paper returns to the initial thoughts, namely that “There is no Planet B.” We must protect the environment that has been entrusted to us, and each of us must contribute using the tools at our disposal — whether through selective waste collection, the use of public transportation, or, for instance, the recycling of PET bottles.

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