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Fused Filament Fabrication Three-Dimensional Printing: Assessing the Influence of Geometric Complexity and Process Parameters on Energy and the Environment

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Abstract: Fused filament fabrication (FFF) 3D printing has been recently adopted in various industries and production processes. Three-dimensional printing (3DP) has gained significant popularity and is being adopted in schools, universities, and fabrication labs, as well as in science, technology, engineering, and mathematics (STEM) education curricula. The aim of this study is to evaluate the energy consumption and environmental impacts of multiple parts with different complexity levels based on various process parameters through FFF printing. This paper focuses on three material filaments: polylactic acid (PLA), tough PLA (T-PLA), and acrylonitrile butadiene styrene (ABS). The influence of geometric complexity, layer height, density, infill pattern, speed, and temperature on energy and the environment will be analyzed through a life-cycle assessment approach. Moreover, this study provides a set of guidelines for 3DP users in education for the energy-efficient and sustainable use of 3D printers. Our results reveal that for the proposed geometries, an energy increase of 8% is recorded for PLA when transitioning from the simple geometry to the very complex one. However, for ABS and T-PLA, no change in energy values due to geometric change is observed. Layer height is found to be the most influential parameter on energy consumption, with an increase of 59%, 54%, and 61% for PLA, ABS, and T-PLA, respectively. Printing temperature, on the other hand, is found to be the least influential parameter on energy and the environment. Furthermore, PLA is found to be the most environmentally friendly material, followed by ABS and T-PLA in terms of climate change, human toxicity, and cumulative energy demand impact categories. However, for the ozone depletion category, ABS contributes the most to environmental damage compared to T-PLA. The results suggest that PLA can be used for visual and prototype models, whereas ABS and T-PLA serve as good candidates for complex end-use applications and functional parts. The presented guidelines will assist 3DP users in the adequate and optimal use of 3DP technology in order to achieve resource efficiency, energy savings, and environmental sustainability.

Keywords: sustainability; energy consumption; FFF 3D printing; fused filament fabrication; education; life-cycle assessment; guidelines

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1. Introduction

Three-dimensional printing (3DP), also referred to as additive manufacturing or rapid prototyping, has gained significant interest among researchers in academia and industry [1,2]. It involves the layer-by-layer assembly of materials to achieve the desired shape, guided by computer-aided design (CAD) [3]. Over time, 3DP has evolved from being primarily a prototyping tool to a full-fledged industrial manufacturing technology, finding applications in diverse sectors such as aerospace, defense, healthcare, and automotive [4,5]. FFF is the leading technology of polymer-based 3DP, thanks to its material-wide availability, cost-effectiveness, and ease of use. One significant area where 3DP plays a fundamental role is in education, particularly with the emergence of fabrication laboratories (Fab Labs)

and STEM education curricula. The concept of Fab Labs is rapidly gaining popularity, inspiring grassroots communities to establish these workshops, as they actively promote 3DP technology and digital fabrication methods and tools for the public [6]. According to recent statistics, the market share of 3DP in the education sector is expected to reach approximately USD 720 million by 2026, signifying a substantial growth trend [7].

Three-dimensional printing has gained recent traction in schools, universities, and libraries, aiming to enhance the teaching and learning experiences [8,9]. The ultimate goal is to foster a dynamic environment that cultivates problem-solving skills and enables profound observation of scientific phenomena [10]. Furthermore, 3DP plays an essential role in boosting active student learning and integrating the concept of sustainability into higher education [11,12]. There are various ways to utilize 3D printing, including but not limited to:

- Hands-on learning: 3DP provides students with a hands-on learning experience, allowing them to design and create their own objects. This hands-on approach fosters better concept visualization, creativity, and problem-solving skills.
- Prototyping and design thinking: 3DP facilitates the iterative design process, empowering students to create rapid prototypes of their ideas, test them, and make improvements. This fosters a culture of innovation, creativity, and an entrepreneurial mindset.
- Special Education: 3DP holds immense potential for producing tactile models, assistive devices, visual aids, and customized learning materials for students with special needs. This actively engages students and enhances the accessibility of inclusive education.
- Entrepreneurship and innovation: 3DP nurtures the entrepreneurial spirit among students by enabling them to design and manufacture their own products. This encourages creative thinking, the identification of market needs, and the exploration of business opportunities, and promotes innovation and self-initiative.

Several studies have been conducted to investigate the effect of process parameters on the mechanical behavior of 3D prints [13–15]. However, a limited number of studies can be found in the literature that evaluate the influence of these parameters on energy consumption and environmental impacts. Kumar et al. [16] compared the environmental impacts of ABS, PLA, and PETG materials of FFF. The authors found that PETG is the most environmentally friendly material, whereas ABS is the least. Moreover, the recycling life-cycle stage accounted for the highest environmental impacts. Another study by Ma et al. [17] assessed the environmental impacts of the fused filament fabrication of PLA in terms of global warming potential, cumulative energy demand (CED), and abiotic depletion under various process parameters. The parameters included layer height, fill density, speed, and temperature. The authors stated that the optimization plan of switching to a high layer height and a larger nozzle diameter would reduce the impact on the environment. Similarly, Warke et al. [18] explored the effect of layer thickness, infill density, and speed on the printing time and energy consumption of FFF for ABS and PLA materials. The authors mentioned that ABS consumes almost double the energy needed for PLA. Although ABS is weaker than PLA, it has high heat resistance. Similarly, Enemuoh et al. [19] investigated the effect of printing process parameters on the energy consumption and physical and mechanical properties of FFF printing. The authors suggested the following optimal parameter levels that generate minimum energy use: 0.3 mm layer thickness, 20% infill density, triangle infill pattern, and a print speed of 80 mm/s. Furthermore, different environmental impacts were evaluated for PLA, ABS, Polyethylene Terephthalate (PETG), and UV resin in Ulkir's study [20]. The authors determined that UV resin is the least harmful material for the environment, whereas ABS is the most harmful material. The selection of material filament is a critical parameter, as it directly influences the quality of the fabricated part and the environmental damage associated with it.

Although 3DP offers several advantages for educational institutions and enhances learning processes, the uncontrolled and wide adoption of 3DP is leading to massive environmental impacts, which directly affect the Earth's resources. Three-dimensional printing in education is still in its exploratory stage, and currently, there are no standard guidelines

or established manuals that exist in the educational 3DP context [21]. Consequently, further research is necessary to analyze the sensitivity of the results in relation to modifications of process parameters. Conducting detailed assessments and designing experiments will enable the accurate evaluation and optimization of environmental metrics [17,22].

To the best of the authors' knowledge, the current literature lacks studies that investigate the influence of geometry complexity and printing process parameters on the environmental assessment of FFF for ABS, PLA, and T-PLA thermoplastics. Therefore, this study aims to address this gap and provide guidelines for 3DP users in the education sector for optimal process parameters and material selection for 3DP. The life-cycle assessment results of three different materials, including polylactic acid (PLA), tough PLA (T-PLA), and acrylonitrile butadiene styrene (ABS), will be analyzed. This research aims to achieve the following objectives:

1. Investigate the impact of part geometric complexity and printing process parameters on the energy consumption of FFF.
2. Conduct a life-cycle assessment for multiple parts with different characteristics and process parameters based on eight main impact categories: climate change, human toxicity, cumulative energy demand, ozone depletion, water depletion, freshwater ecotoxicity, fossil depletion, and agricultural land occupation.
3. Provide guidelines for 3DP users in education, STEM initiatives, and Fab Labs, aiming to promote efficient resource utilization and sustainable technology practices.

The rest of this paper is organized as follows. Section 2 presents the research methodology, including the experimental setup and LCA methodology. Section 3 provides the results of energy and LCA analyses, the discussion, and sustainable guidelines for 3DP users. Finally, in Section 4, the conclusions, limitations of the study, and suggestions for future research are provided.

2. Materials and Methods

The research methodology employed in this study is outlined in Figure 1 in a step-by-step manner. LCA is a widely recognized approach utilized to evaluate the environmental impacts of a product or system throughout its life cycle. In this paper, the selected part to be analyzed is mechanical gears. Gears were chosen as the subject of study due to their diverse types and corresponding variations in geometric complexity. Figure 2 illustrates the five gear types selected, arranged in ascending order of complexity from left to right. To acquire the necessary computer-aided design (CAD) models of the geometry, the GrabCAD platform was utilized [23]. Furthermore, Cura UltiMaker was employed as the slicing software [24].

2.1. Experimental Setup and Design

In this experiment, three different material filaments were used, namely UltiMaker ABS, UltiMaker PLA, and UltiMaker T-PLA. Table 1 presents the material properties associated with each filament. It should be noted that the filament manufacturer (UltiMaker) provided the melting temperature range for each material.

Table 1. Material properties of FFF materials.

Material	Melting Temp Range (°C)	Density ($\frac{g}{cm^3}$)	Diameter (mm)	Thermal Resistance (°C)
UltiMaker PLA	[200, 210]	1.24		59
UltiMaker ABS	[225, 260]	1.1	2.85 ± 0.10	87
UltiMaker Tough PLA	[210, 220]	1.24		58

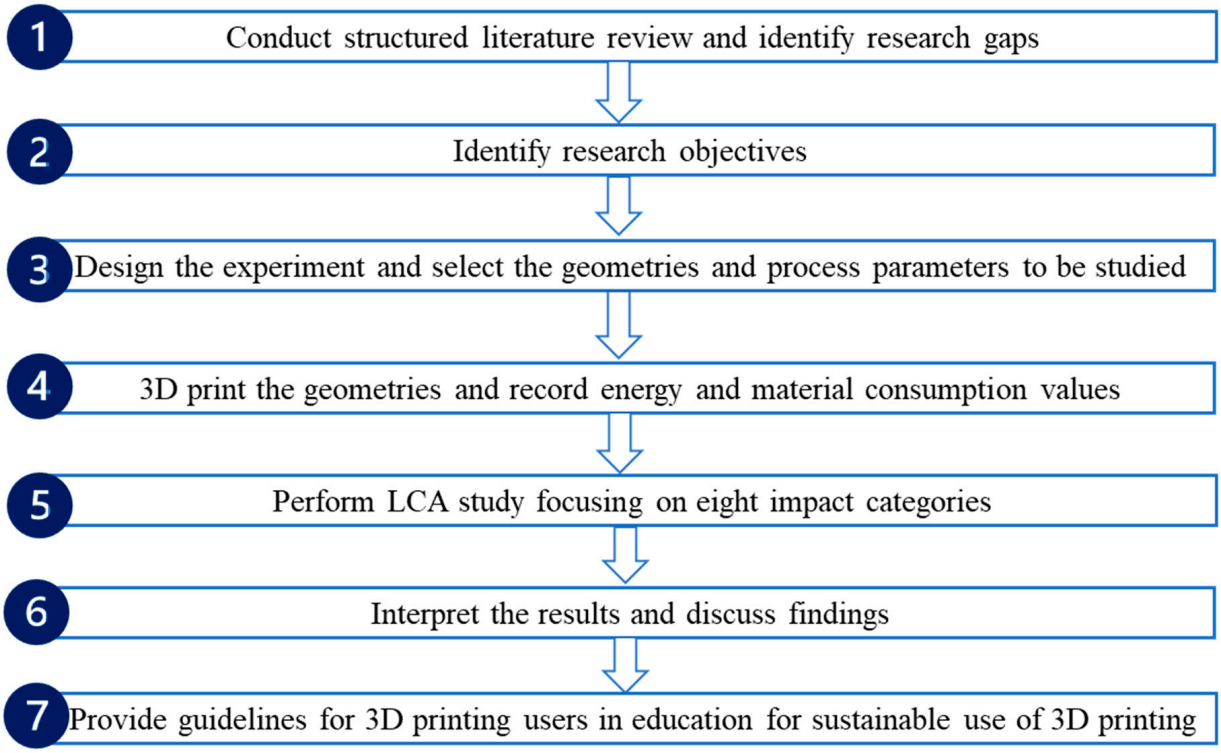


Figure 1. Research methodology flowchart.

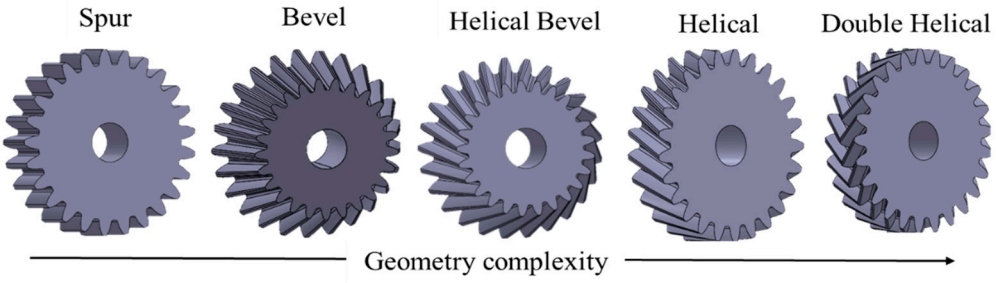


Figure 2. Geometric complexity of gears from simple to complex.

Figure 3 shows the experimental setup used for this study. All test sample gears were fabricated using the FFF printing technique on an UltiMaker 2+ Connect single extruder with a build volume of 223 × 220 × 205 mm. A digital power meter with a power accuracy of 0.1 watts was utilized in order to obtain the electric energy consumption in kWh for each 3D-printed gear. Additionally, an infrared thermometer was used to measure the temperature of both the print bed and nozzle prior to initiating each print. It is worth noting that each part was printed once the nozzle temperature had cooled down to around 25 to 27 degrees for all materials, and the bed temperature reached 40–42 degrees for PLA and T-PLA, and 50–52 degrees for ABS.

The default parameters used in the experiment are listed in Table 2. Throughout this study, five printing process parameters were utilized and selectively adjusted to examine their impact on energy consumption and environmental impacts (Table 3). The temperature values were adjusted based on the guidelines provided by UltiMaker to ensure the proper use of the filaments. It is important to note that the remaining process parameters were kept at their default values whenever any parameter was modified. The investigated process parameters are further explained as follows:

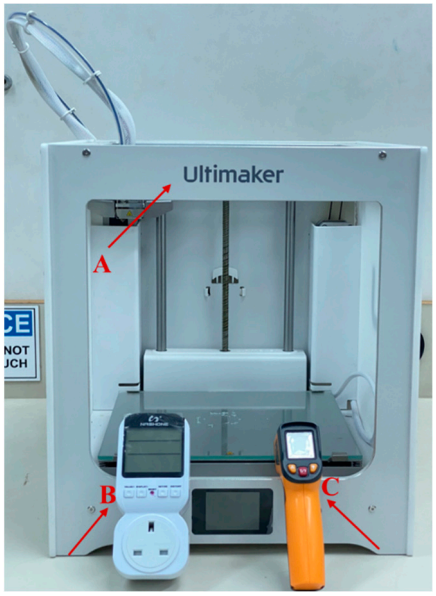


Figure 3. Experimental setup (A) 3D printer, (B) digital power meter, (C) infrared thermometer.

1. Layer height: The layer height, also known as the layer thickness, represents the vertical dimension of each deposited layer along the *z*-axis [25]. It is recommended that the layer height should not be less than 20% or exceed 80% of the nozzle diameter. In our study, the printer we used has a nozzle diameter of 0.4 mm, which sets the range of the layer height to be [0.08, 0.32] mm. Therefore, the selected variations for the layer height were 0.1 mm, 0.2 mm, and 0.3 mm.
2. Infill density: The infill density represents the total amount of printing material inside the printed part's periphery and is measured as a percentage [26]. The selected variations for the infill percentage were 30%, 60%, and 90%.
3. Infill pattern: The infill pattern refers to the geometry and structure of the inside material of the part [27]. For this study, infill patterns were selected according to the UltiMaker category guidelines for infills, namely strong 2D, quick 2D, strong 3D, and flexible 3D [28].
4. Printing temperature: The printing temperature is determined by the processing temperature of the consumable material used. Higher printing temperatures promote better fluidity of the material during the printing process [17]. In this study, printing temperatures were varied based on the range provided by the manufacturer.
5. Printing speed: The printing speed refers to the horizontal speed of the nozzle on the build platform during extrusion and deposition [13]. Printing speeds were varied by ±10 mm in this experiment.

Table 2. Default parameters.

Parameter	Value		
Layer Height (mm)		0.2	
Infill pattern		lines	
Infill density		30%	
Material consumption (g)		3	
Build plate adhesion type		Skirt	
Material	PLA	T-PLA	ABS
Temperature (°C)	210	225	250
Printing speed (mm/s)	60	40	55

Table 3. Range of change of process parameters.

Process Parameter	Range of Change		
Material	PLA	T-PLA	ABS
Printing temperature (°C)	[190–230]	[205–245]	[240–260]
Printing speed (mm/s)	[50–70]	[30–50]	[45–65]
Layer height (mm)		[0.1–0.3]	
Infill percentage		[30–90%]	
Infill pattern		Lines, grid, cubic and concentric	

2.2. Environmental Life-Cycle Assessment

According to ISO 14044 [29], LCA has four main stages: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and results interpretation [30].

2.2.1. Goal and Scope Definition

The aim of this study is to assess the environmental impact of producing different gear parts using three filament materials and various process parameters through FFF 3D printing. The functional unit used in this study was the simple geometrical gear, that is, the spur gear. Cradle-to-gate was adopted as the system boundary of this study (Figure 4). The processes considered for the LCA analysis were raw material extraction, raw material processing, transportation, and product manufacturing. The environmental impacts associated with the use and end-of-life stages of the parts were not included in the scope of the study.

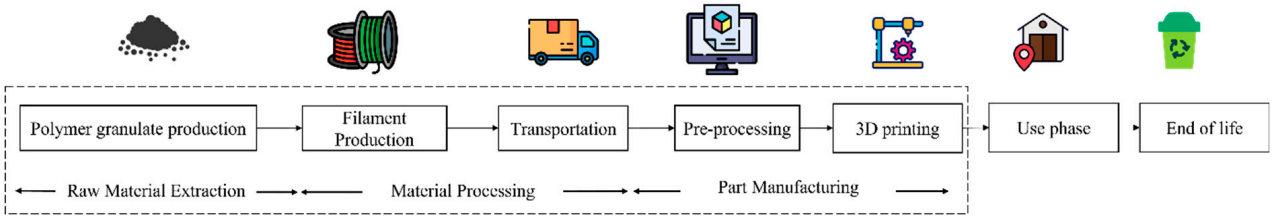


Figure 4. System boundary of the study: cradle-to-gate.

2.2.2. LCI

Life-cycle inventory analysis captures the physical materials and energy flows that enter and leave the system. In this research, the Ecoinvent v3.8 life-cycle inventory database was utilized to extract the background process data [31]. The foreground data associated with the product system were obtained through laboratory printing experiments.

For the extrusion of PLA and ABS material filaments, the energy requirements are 5.94 MJ/kg and 6.08 MJ/kg, respectively [32]. Regarding T-PLA, there are various processes that can be employed to enhance its toughness, such as blending with polymers, adding nanoparticles or fibers, and annealing or heat treatment. In this study, it was assumed that PLA had been toughened through the annealing process. We assumed that annealing 1 kg of PLA at 60 degrees for 2 h required 324 MJ/kg of energy. Table 4 shows a sample of LCI data for a functional unit of 3 g (spur gear) at each life-cycle stage.

Table 4. Inventory data for a functional unit of 3 g.

Material/Activity	Unit	PLA	ABS	T-PLA
Raw material production	kg	0.003	0.003	0.003
Extrusion of filament	kWh	5×10^{-6}	5.07×10^{-6}	2.75×10^{-4}
Transportation	tkm	0.0146	0.0146	0.0146
3D printing	kWh	0.038	0.055	0.049

2.2.3. LCIA

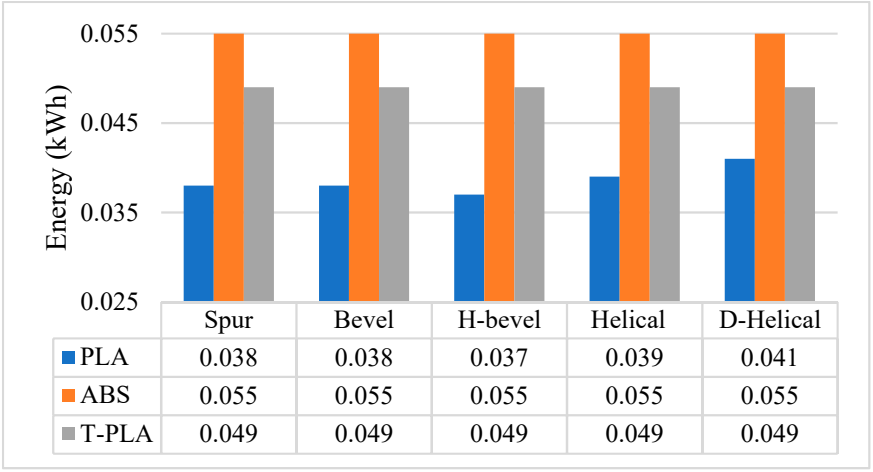
In LCIA, the impacts induced by LCI are evaluated after assigning them to certain impact categories. The impact assessment method adopted in this study was ReCiPe Midpoint (E), with (E) representing the egalitarian perspective. The ReCiPe method comprises 18 different midpoint indicators; however, only seven indicators were analyzed in this study: climate change, human toxicity, ozone depletion, water depletion, fossil depletion, freshwater ecotoxicity, and agricultural land occupation. Furthermore, the cumulative energy demand (CED) method was employed in this study. The CED method considers the sum of eight impact categories, including renewable biomass, non-renewable fossil fuels, renewable geothermal energy, non-renewable nuclear energy, non-renewable primary forest, renewable solar energy, renewable water energy, and renewable wind energy. These categories collectively provide a comprehensive assessment of the energy demand throughout the life cycle of the analyzed gear parts.

3. Results and Discussion

3.1. Experimental and Energy Results

The energy consumption values were measured for the five different gear geometries when 3D printed using the three materials, as illustrated in Figure 5. The resulting 3D-printed test samples are shown in Figure 6, where ABS, T-PLA, and PLA filaments are represented by silver-grey, black, and green colors, respectively. It can be observed that the energy consumption values for the ABS and T-PLA prints remained constant regardless of any changes in geometry. The geometric complexity had a minimal impact on the energy consumption of the ABS and T-PLA materials. However, for the PLA parts, there was a slight increase in energy consumption with higher geometric complexity. The spur, bevel, and H-bevel gears exhibited similar energy consumption levels due to their similar geometries. In contrast, the helical and double-helical gears showed increases in energy consumption of 2.6% and 7.9%, respectively. These increases were expected, as the teeth of the helical gear are bent into a helix shape, while the total face of the d-helical gear is made into two halves with the same helix angle but with opposite hands [33]. Consequently, more energy is required to produce helical and double-helical gears due to their specific geometrical characteristics.

The five studied gear geometries were imported into Cura software version 5.2.1, taking into account the variations in the process parameters discussed in the previous section. The production of these gears was carried out using three different filaments. The energy consumption values corresponding to each process parameter are presented in Figure 7, along with an illustration of the impact of each parameter on the energy consumption of the spur gear. In the following section, a detailed discussion of the results is presented for each individual parameter.



	Spur	Bevel	H-bevel	Helical	D-Helical
PLA	0.038	0.038	0.037	0.039	0.041
ABS	0.055	0.055	0.055	0.055	0.055
T-PLA	0.049	0.049	0.049	0.049	0.049

Figure 5. Energy values for different complexity levels of gears.

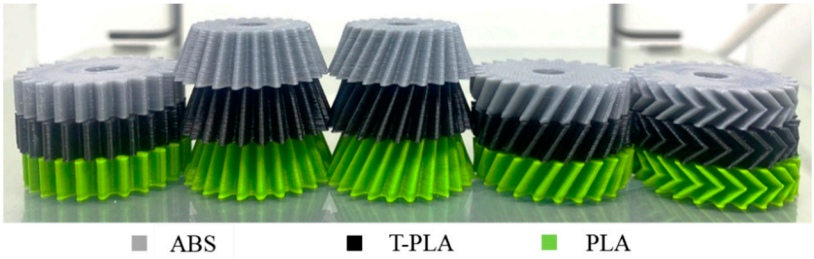


Figure 6. Test samples of 3D-printed gear geometries for three materials.

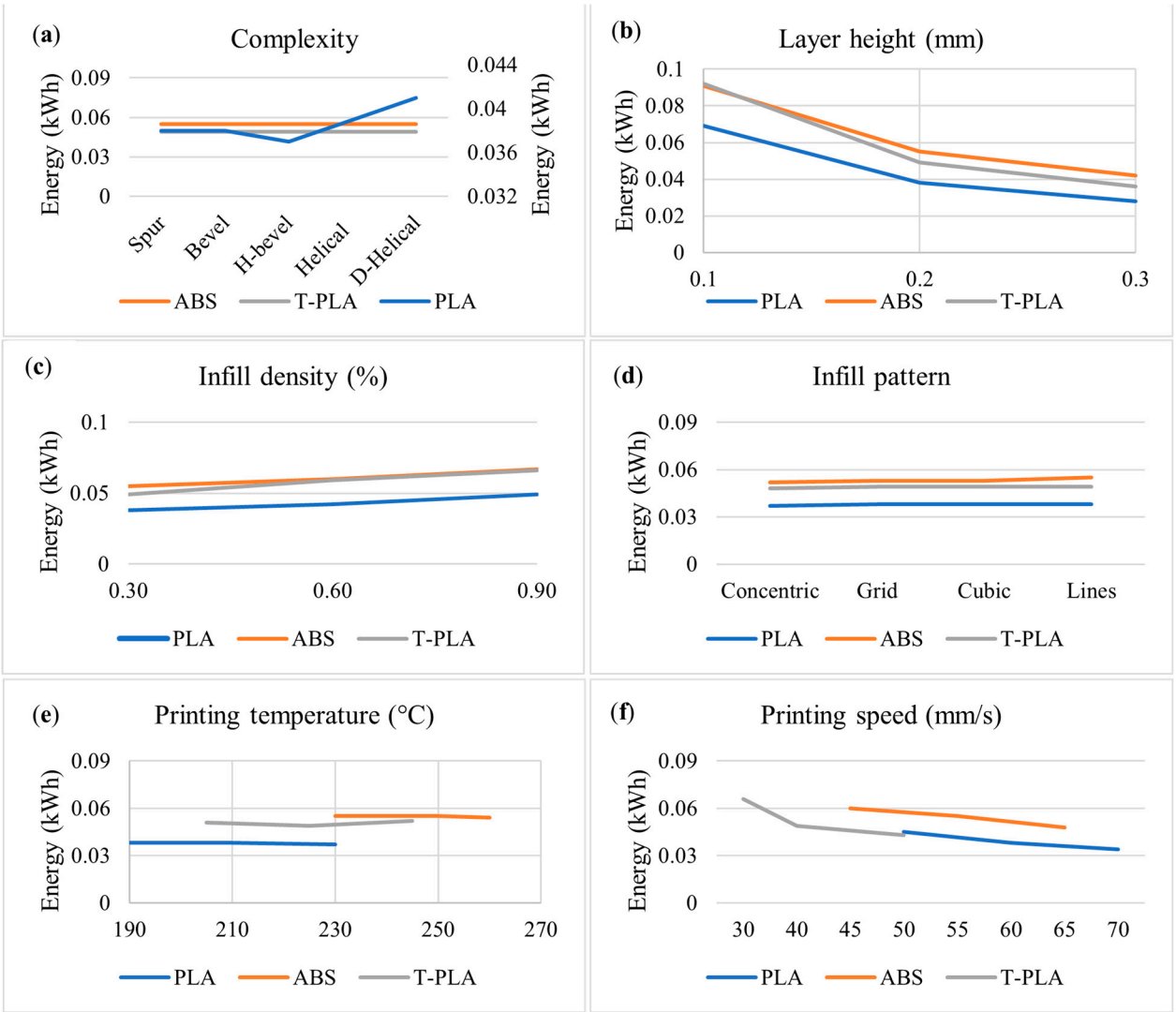


Figure 7. Energy consumption values of the spur gear for (**a**) complexity, (**b**) layer height, (**c**) infill density, (**d**) infill pattern, (**e**) temperature, and (**f**) speed.

1. Layer height: According to the findings presented in Table S1, a noticeable increase in energy consumption can be observed as the layer height decreases for all materials. Thinner layer heights resulted in an improved surface finish but required higher energy input. On average, the energy values decreased by approximately 59% for PLA, 62% for T-PLA, and 54% for ABS with an increase in the layer height. A visual representation of the relationship between the layer height and energy consumption is provided in Figure 7b. It can be seen that when the layer height is set to 0.1 mm, the energy values for ABS and T-PLA are almost identical, whereas PLA consistently

exhibits the lowest energy consumption. As mentioned earlier, when the layer height is increased to 0.3 mm, the energy values for ABS and T-PLA remain relatively similar across different geometries. However, a significant change in energy values can be observed when the layer height is set to 0.1 mm. Therefore, it can be concluded that the ABS and T-PLA materials are more sensitive to changes in geometric complexity when using lower layer heights. Similarly, for PLA, a 9% increase in energy consumption can be observed between the simple spur gear and the complex D-helical gear when the layer height is 0.1 mm, which is lower compared to the 14.2% increase observed when the layer height is 0.3 mm. So, changes in energy due to geometric complexity are more sensitive when adopting higher layer heights.

2. Infill density: The relationship between infill density and energy consumption is relatively straightforward. As the density increases, more material is used, which leads to longer printing times and, consequently, higher energy consumption. Table S2 reveals an interesting observation: when the infill density reaches 90%, the energy consumption becomes less sensitive to geometric complexity. This is evident from the similar energy values for the spur and d-helical gears at a density of 90% across all three materials. When the infill density is set at 30%, ABS prints require more energy compared to T-PLA. However, as the density increases, the energy consumption for both materials becomes roughly equivalent. This can be attributed to the fact that as the infill density increases, the printed part requires more heat energy to melt and fuse the additional material.
3. Infill Pattern: In Table S3, it is evident that the energy consumption shows little sensitivity to changes in the infill pattern. This is indicated by the fact that energy values fall within a similar range when different infill patterns are used across all three materials. Furthermore, Figure 7d demonstrates that the line infill pattern has the greatest impact on energy consumption, followed by the cubic infill pattern, compared to the other patterns. However, it is worth noting that, in general, the choice of infill pattern does not have a significant effect on energy consumption.
4. Printing temperature: Table S4 provides insights into the relationship between temperature and energy consumption for the three materials. A marginal change in energy consumption can be observed as the temperature increases. Specifically, for PLA, there appears to be an inversely proportional relationship between temperature and energy consumption, with only an 8% increase in energy recorded for a temperature variation of 40 °C. Similarly, ABS and T-PLA exhibit only slight changes in energy values. Figure 7e further illustrates the consistent behavior of energy values across different temperatures. These findings align with previous research conducted by Elkaseer et al. [34] and Vidakis et al. [35], where they mentioned that the change in energy consumption due to temperature variation is insignificant and considered marginal for ABS and PLA thermoplastics. It is worth noting that PLA exhibited the lowest energy values, whereas ABS exhibited the highest. This observation was expected, as ABS has a higher melting temperature compared to PLA and T-PLA.
5. Printing speed: The relationship between printing speed and energy consumption can be described as inversely proportional. In other words, higher printing speeds correspond to lower energy consumption. According to Table S5, increasing the speed by 20 mm/s resulted in an average decrease in energy consumption of 20%, 36%, and 16% for PLA, T-PLA, and ABS, respectively. It is worth noting the interesting observation that the energy values for printing PLA and T-PLA were equivalent at a speed of 50 mm/s, despite T-PLA having a higher melting temperature. This finding suggests that T-PLA can be a beneficial choice for achieving low energy consumption during the printing process. The results highlight the significant impact of printing speed on energy consumption, with higher speeds leading to reduced energy requirements.

3.2. LCA Results

LCA analysis was conducted using the ReCiPe and CED methods for the spur gear, considering climate change (CC), human toxicity (HT), cumulative energy demand (CED), ozone depletion (OD), water depletion (WD), fossil depletion (FD), freshwater ecotoxicity (FET), and agricultural land occupation (ALO) impact categories. Figure 8 presents the contribution of the three life-cycle stages for all three materials, excluding transportation, which was assumed to be similar for all materials. It should be noted that the RM processing category is plotted in the secondary *y*-axis for the sake of data clarity.

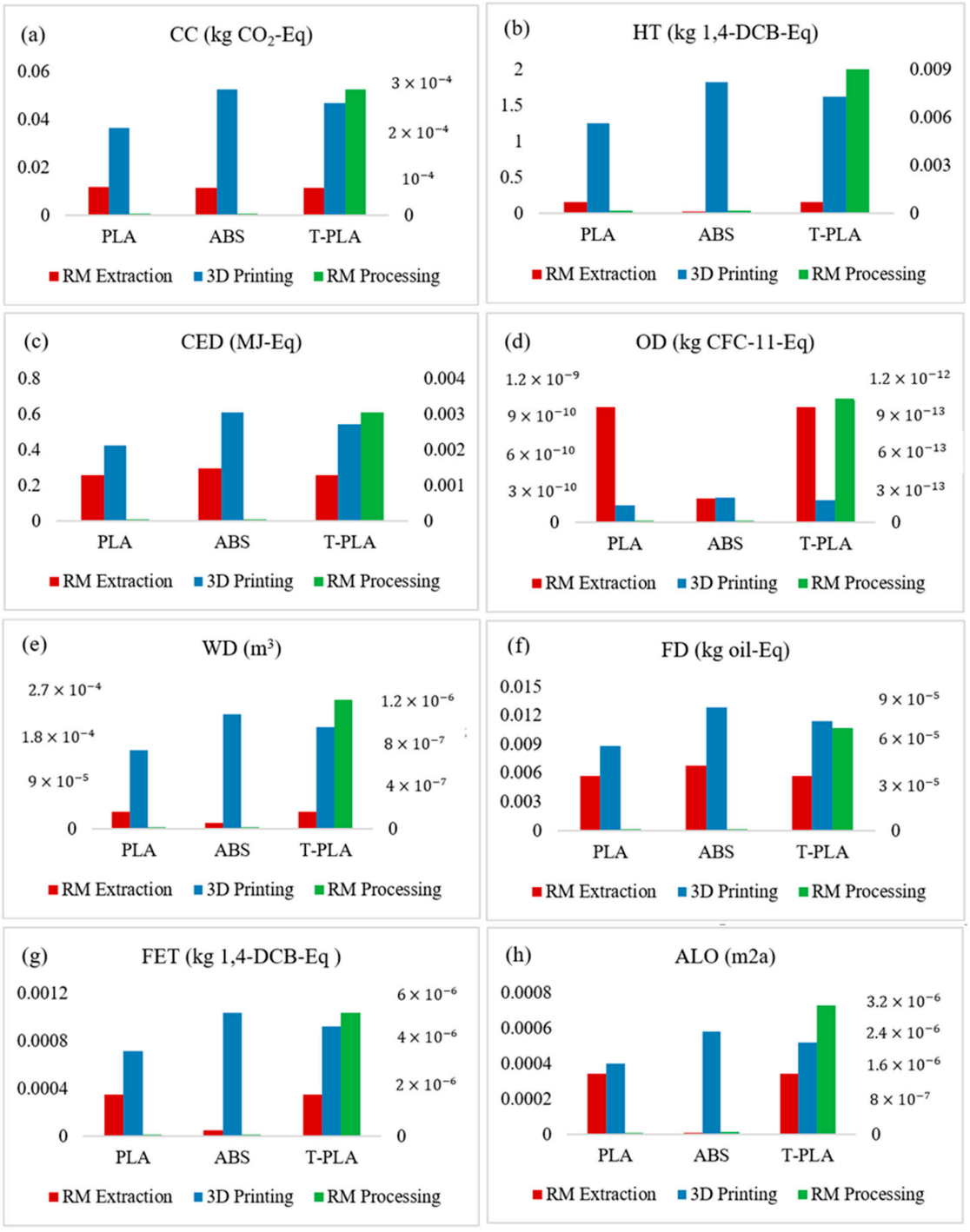


Figure 8. Mid-point assessment results of the spur gear for (**a**) CC, (**b**) HT, (**c**) CED, (**d**) OD, (**e**) WD, (**f**) FD, (**g**) FET and (**h**) ALO impact categories.

In terms of the carbon footprint for the climate change (CC) impact category, PLA consistently exhibited the lowest environmental impact across all three life-cycle stages (Figure 8a). On the other hand, ABS demonstrated the highest carbon footprint in the 3D-printing activity, as previously discussed in relation to Figure 5. Regarding the raw material processing stage, T-PLA outweighed the other materials, primarily due to the annealing process involved in producing tough PLA. In Figure 8b, it can be seen that the contribution of extracting PLA and T-PLA on human toxicity (HT) is approximately 10 times greater compared to ABS. However, the values associated with raw material processing are relatively insignificant for all three materials. Regarding 3D printing, ABS and T-PLA have higher contributions compared to PLA. For the CED, the RM extraction of ABS is higher than that of PLA, which may be due to the energy-intensive emulsion and polymerization of styrene, acrylonitrile, and polybutadiene. Furthermore, in terms of the OD impacts shown in Figure 8d, the extraction of PLA has the greatest impact, exceeding the impact of 3D-printing ABS. This indicates that the extraction phase of PLA has a more significant contribution to ozone depletion compared to the 3D-printing process of ABS.

In Figure 8e,g, we can see that PLA has the highest contribution to raw material extraction for the water-related categories, namely water depletion and freshwater ecotoxicity. This can be attributed to the water-intensive process of PLA production from sugarcane, wheat, and sugar beet [16]. Similarly, for the agricultural land occupation (ALO) impact category, the extraction of both PLA and T-PLA has the most significant impact on land use compared to ABS.

In summary, the LCA results suggest the use of PLA, as it is the most environmentally friendly material. However, for certain impact categories, such as OD, FET, and WD, the process of extracting PLA has a significant impact compared to ABS. T-PLA impacts are similar to those of PLA, except for the raw material processing stage of T-PLA, which is high energy consuming due to the process of toughening the PLA.

These findings emphasize the environmental advantages of PLA, which exhibits a lower carbon footprint throughout its entire life cycle compared to ABS. The LCA analysis supports the notion that PLA is a more environmentally friendly choice for 3D-printing applications, considering its reduced environmental impact. Overall, these results highlight the varying environmental impacts associated with the different stages of the life cycle for each material, shedding light on the importance of considering specific environmental implications at different stages of material processing and 3D printing.

LCA Results per Parameter

This section presents the LCA results for the spur gear (functional unit), considering the aspects of geometric complexity and printing parameters for all three materials. The analysis focuses on two impact categories, namely climate change and human toxicity.

- Complexity

In terms of geometric complexity, the environmental impacts of only the PLA material are illustrated below, as the T-PLA and ABS printed gears showed equivalent energy values (Figure 5), and therefore, their environmental results are expected to be equivalent. Figure 9 specifically focuses on the 3D-printing phase, as the other phases remain identical for parts with the same material consumption. The results indicate that the first three gears, namely the spur, bevel, and h-bevel, have lower environmental impacts compared to the helical gears. This can be attributed to the higher energy consumption associated with increased gear complexity. As we transitioned from simpler geometries (spur) to more complex ones (D-helical), the CC and HT impacts increased by approximately 6% and 7%, respectively.

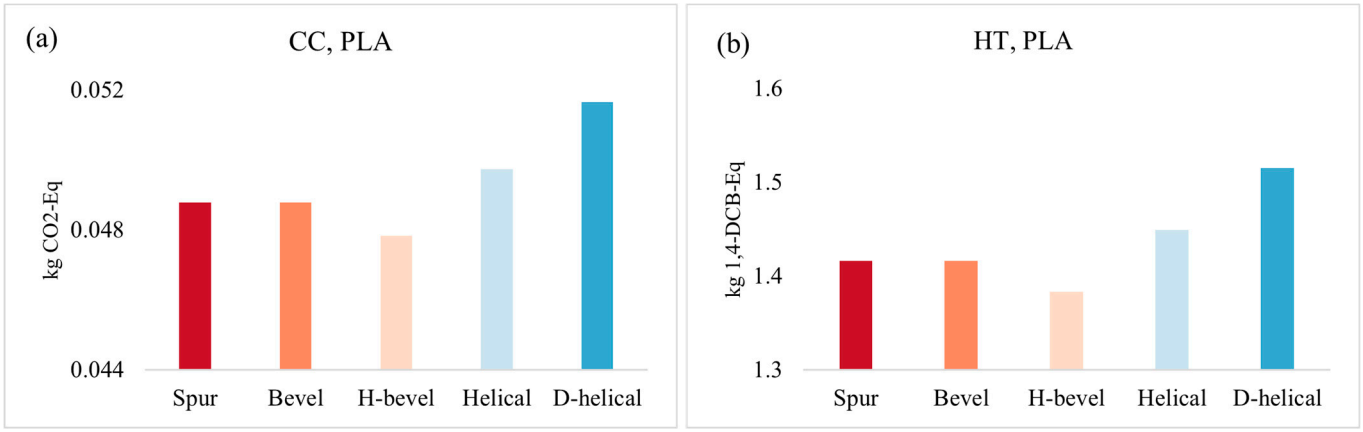


Figure 9. Mid-point assessment results for complexity factor in terms of (**a**) CC and (**b**) HT.

- Layer height

In Figure 10, the mid-point results for the three materials are presented with respect to the varying layer heights. It can be observed that all three materials exhibit a similar trend, where the environmental impact decreases as the layer height increases. Specifically, when the layer height decreases from 0.3 mm to 0.1 mm, the carbon footprint nearly triples, resulting in increases of 146%, 117%, and 156% for PLA, ABS, and T-PLA, respectively. These findings highlight the importance of selecting an appropriate layer height to optimize environmental performance during the 3D-printing process.

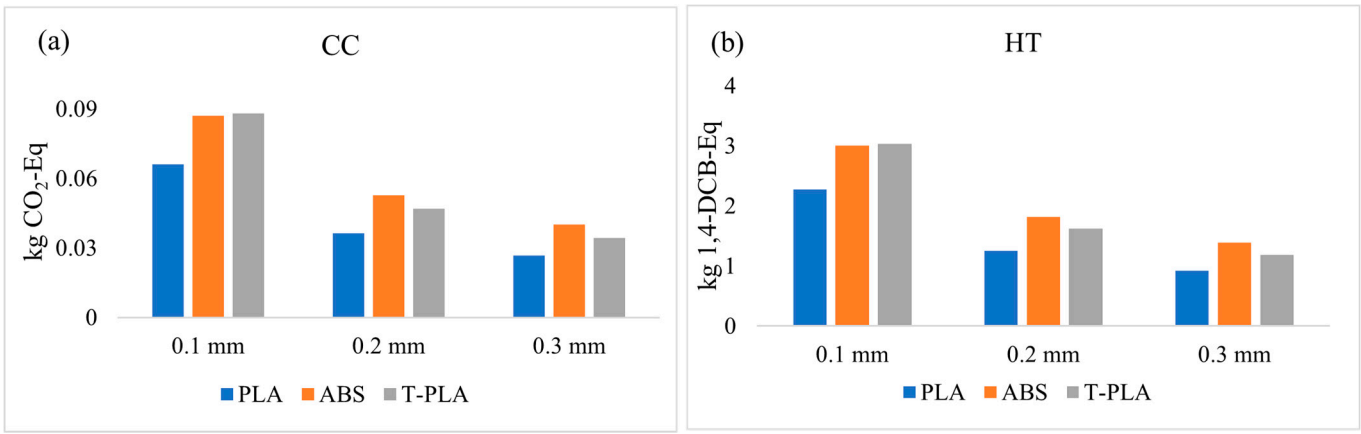


Figure 10. Mid-point assessment results of layer height factor in terms of (**a**) CC and (**b**) HT.

- Infill density

Figure 11 shows the LCIA results for varying infill densities for PLA, ABS, and T-PLA, respectively. It should be noted that the extrusion category is plotted on the secondary *y*-axis for the sake of data clarity. The graph shows increases in the three stages: raw material production, extrusion, and 3D printing. The reason behind this is the increase in the part's weight and material consumption, along with the increase in energy needed for 3D printing. For the three materials, the extraction of the raw materials contributes more in terms of CC damage compared to 3D printing, whereas RM extraction contributes much less to the human toxicity impact category.

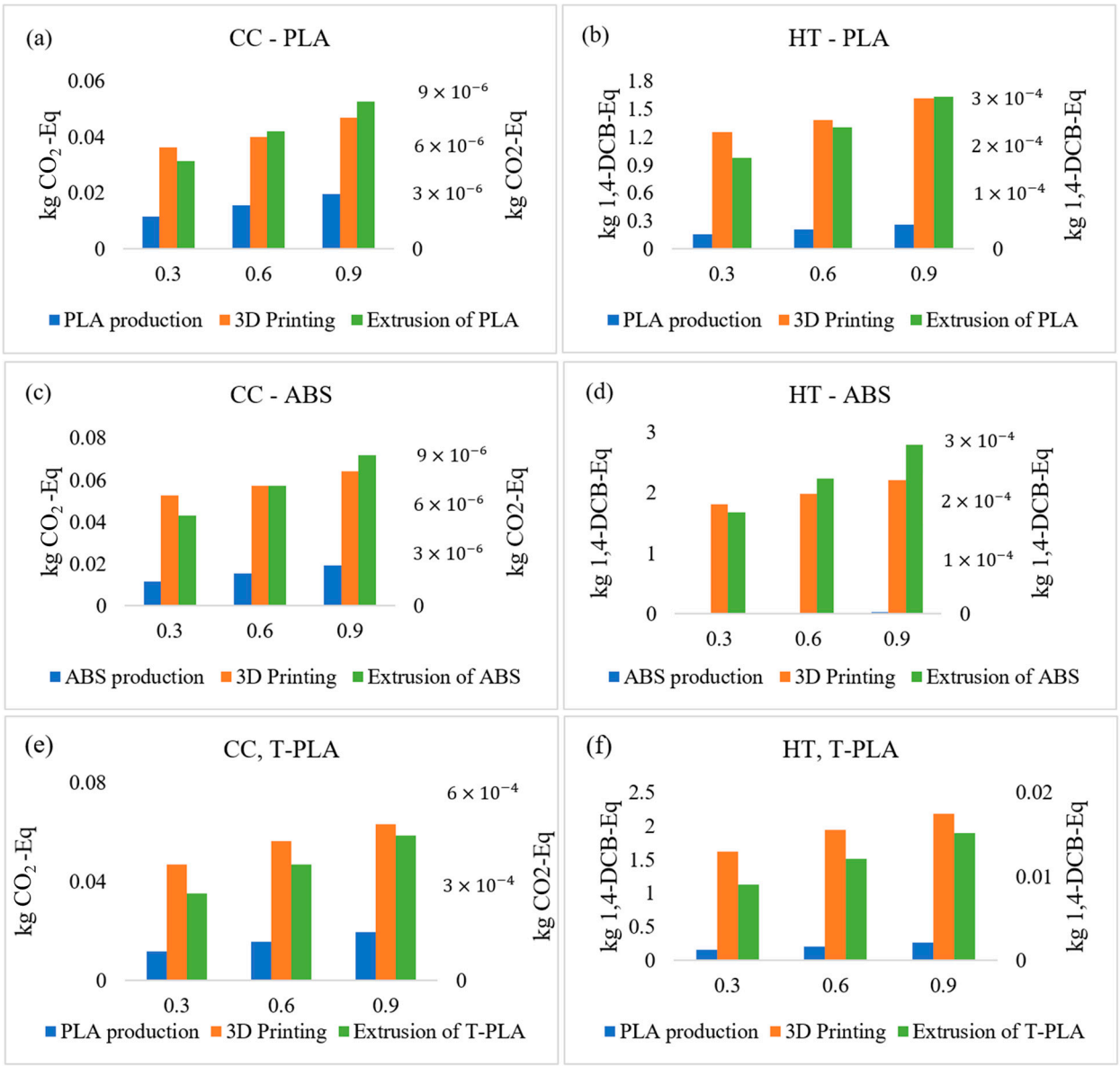


Figure 11. Mid-point assessment results of infill density factor for (**a**,**b**) PLA, (**c**,**d**) ABS, and (**e**,**f**) T-PLA in terms of CC and HT.

- Infill pattern

Figure 12 demonstrates the environmental impacts of changing the infill pattern. The results indicate that although the line infill pattern has the highest contribution to environmental damage, the differences between the other infill patterns are relatively marginal. Overall, the effect of changing the infill pattern on the environment is considered insignificant.

- Printing speed

Figure 13 presents the results for climate change (CC) and human toxicity (HT) impacts during the 3D-printing stage when the printing speed is increased for the three materials. A consistent trend can be observed across all three materials. The carbon footprint and human toxicity exhibit an inverse relationship with the printing speed. However, it is important to note that there is a limit to increasing the printing speed, as excessively high speeds can negatively affect the surface finish of the printed part. These findings highlight the trade-off between environmental impacts and the quality of the printed part. Although

higher printing speeds can lead to reduced environmental impacts, it is crucial to find a balance to avoid compromising the surface finish and ensure the desired quality of the printed object.

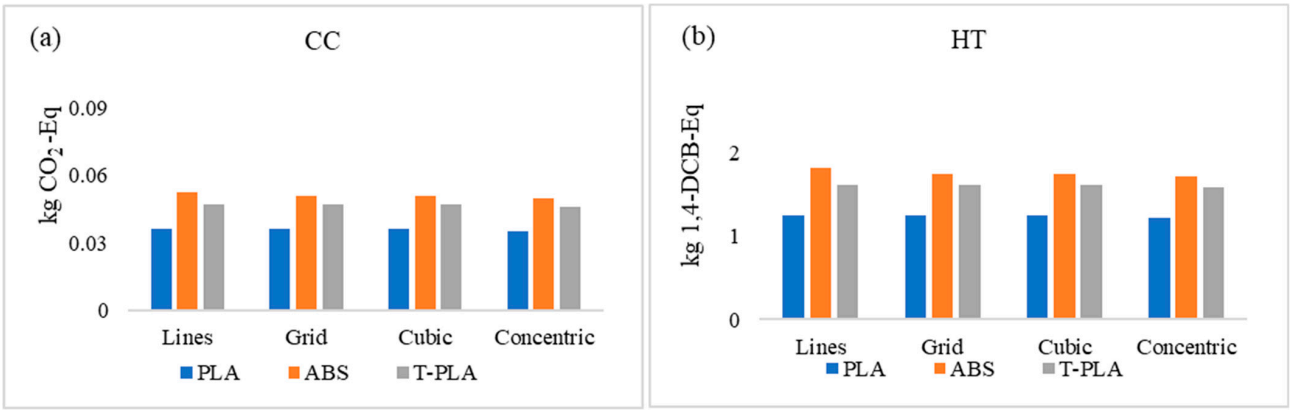


Figure 12. Mid-point assessment results of infill pattern factor in terms of (**a**) CC and (**b**) HT.

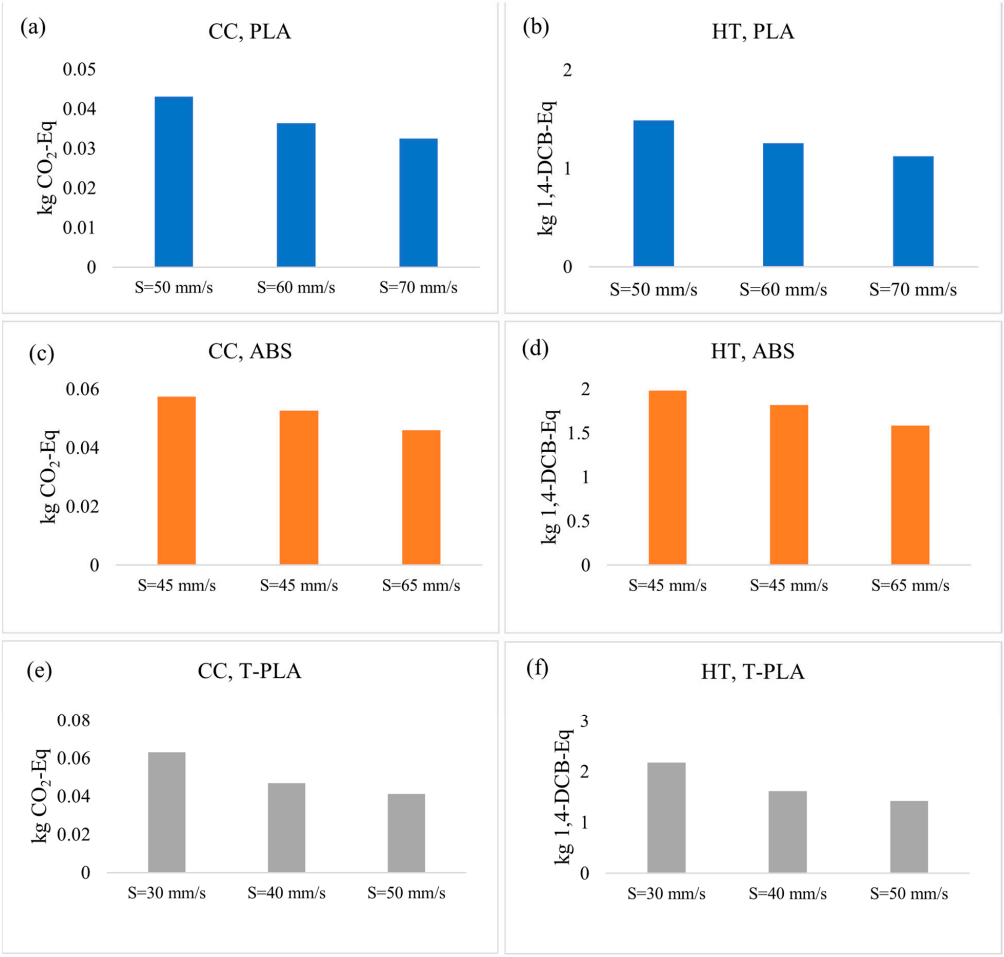


Figure 13. Mid-point assessment results of the speed factor for (**a**,**b**) PLA, (**c**,**d**) ABS, and (**e**,**f**) T-PLA in terms of CC and HT.

- Printing temperature

The influence of temperature on the environmental impacts was found to be marginal, similar to the observed changes in energy consumption discussed in the previous sub-

section, as illustrated in Figure 14. The results indicate that variations in temperature have a limited effect on the environmental impacts during the 3D-printing process. The changes in the environmental impacts due to temperature fluctuations are relatively minor and may not significantly alter the overall environmental performance of the printing process.

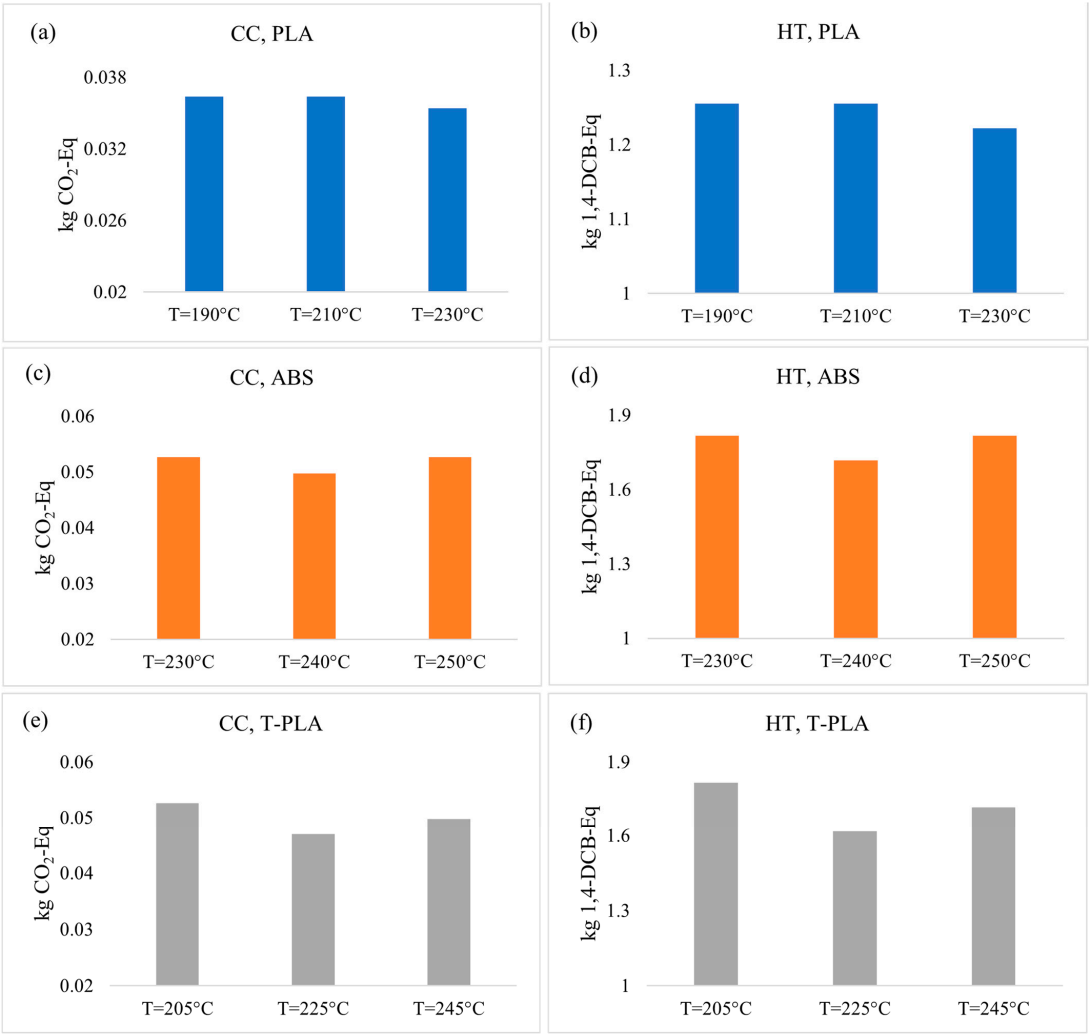


Figure 14. Mid-point assessment results of temperature for (**a**,**b**) PLA, (**c**,**d**) ABS, and (**e**,**f**) T-PLA in terms of CC and HT.

3.3. Discussion

The analysis of energy consumption and life-cycle impact assessments, considering the geometric complexity and various process parameters for three different materials, reveals key insights into the energy efficiency of 3D printing. Among the studied parameters, the layer height stands out as having the most significant impact on energy consumption, human toxicity, and climate change. Particularly, the lowest layer height of 0.1 mm resulted in the highest energy consumption across all three materials.

Table 5 highlights that the largest percentage increase in energy consumption is observed for T-PLA when the layer height is reduced. T-PLA, characterized by a high melting temperature and slower printing speed compared to ABS, surpasses ABS as the most energy-intensive material. Following T-PLA, ABS is the second-most energy-consuming material, as it is a petroleum-based plastic and has a high specific heat capacity [16].

Furthermore, the experimental results indicate that geometric complexity tends to increase energy consumption and environmental impacts, particularly in cases involving complex features or notches, such as the helical and D-helical gears. Overall, the most

influential parameters affecting energy consumption include layer height, infill density, and speed. However, changes in energy consumption and environmental impacts resulting from temperature and geometric complexity variations are found to be marginal and insignificant, with changes of less than 10%.

Table 5. Percent increase in spur gear energy consumption between the upper and lower bounds of each parameter.

	PLA	T-PLA	ABS
Complexity	8%	0%	0%
Layer height (mm)	59%	61%	54%
Infill density (%)	29%	35%	22%
Temperature (°C)	3%	2%	4%
Speed (mm/s)	24%	35%	20%

Comparing different filament materials and considering the comprehensive assessment of LCA analysis, PLA emerges as a preferable choice due to its favorable environmental profile across various process parameters. However, it is important to note that the extraction of raw materials for PLA has a higher environmental impact in terms of HT, OD, FET, and WD compared to ABS. One key observation regarding T-PLA is that the processing of raw PLA material has a significant impact due to the energy required for the annealing process. To enhance the toughness of PLA, several methods can be employed, such as fiber reinforcement, polymer blending, and heat treatment.

In order to make well-informed material choices, it is crucial to thoroughly evaluate the specific impact categories and stages of material processing. This assessment can provide a comprehensive understanding of the environmental implications associated with each material, allowing for a more sustainable decision-making process.

3.4. Guidelines for 3DP Users in Education

Three-dimensional printing is gaining significant interest in the education sector, with its adoption spreading to schools, universities, Fab Labs, and STEM-based curricula. However, as this technology becomes more widespread, it is necessary to establish control and regulations to mitigate the carbon footprint and environmental harm associated with it. This article aims to provide a set of guidelines for stakeholders in education, STEM, and Fab Labs who are interested in utilizing FFF printing while minimizing the environmental impacts caused by this technology. Based on the carried-out study, Figure 15 presents key aspects that should be considered as guidelines for educators, students, and laboratory managers. These guidelines are designed to promote sustainability and reduce excessive energy consumption and environmental impacts resulting from 3D printing. These aspects are as follows:

- Safety and Ventilation: Considerations for public safety and health are crucial when dealing with any machinery or equipment, including 3D printers. It is important to operate 3D printers with optimal controls and adhere to safety regulations, as this technology can release hazardous particles and vapors into the air [36]. Moreover, the emitted particulate matter from 3D printers, which can contribute to air pollution, should be filtered by incorporating particulate air filters.
- To mitigate the risk of environmental pollution and control emissions and promote a safe and healthy environment for users of 3D printing, it is essential to implement proper exhaust ventilation and air filter systems in the classroom or laboratory where the 3D printer is located. Additionally, ensuring adequate airflow will help maintain a safe and healthy environment.
- Material Selection: The choice of printing material filament directly impacts the environmental footprint. Through conducted experiments, it has been determined that PLA is the least harmful material to the environment. This is due to its biodegradability and its composition of natural sources such as corn and sugarcane. Therefore,

adopting PLA as the printing material is highly recommended. However, if the printed object requires functionality and strength, then T-PLA or ABS should be used. For example, when students utilize 3D printing to fabricate parts for a manufacturing design project or create end-use parts, ABS can be employed for complex and functional components, whereas T-PLA is particularly beneficial for functional prototypes and larger-sized tooling. Conversely, if an educator is solely printing a demonstration for students to visualize a concept, PLA is the recommended choice to minimize environmental impact.

- Waste, Recycling, and Reuse: 3DP users should consider the safe and proper disposal of waste material, including failed prints and support structures. An advantageous aspect of thermoplastics is their ability to be reused. Filament material waste can be recycled, melted, reformed into new filament spools, and utilized as raw material for printing. This practice can significantly reduce the carbon footprint associated with waste disposal, landfill, and incineration, as well as the extraction and processing of raw materials. Consequently, it allows for both resource conservation and energy savings.
- Energy Efficiency: Energy efficiency can be achieved by implementing optimized process parameters. Additionally, increasing the batch size number and consolidating multiple small prints into a single print job can save energy related to the electric heating of the nozzle and bed. Increasing the batch size leads to lower environmental impacts [37].
- Printer Operation and Maintenance: All printers should undergo regular maintenance and inspections to ensure the optimal efficiency of the 3D printer's operation. Well-maintained printers are less likely to experience issues that result in excessive energy consumption. For example, lubricating the printer's moving parts and cleaning and replacing worn-out or clogged components can help reduce energy waste and minimize friction. In addition, it is advisable to adopt energy-saving measures such as utilizing standby mode and turning off the printer during idle times. Furthermore, it is recommended to use the minimum number of 3D printers necessary for maximum activity, as this helps to reduce the energy impact of non-active printers [38].
- Print Process Parameters: A balance of print quality, speed, layer height, and density is necessary, depending on the intended purpose of the print, to ensure resource efficiency and minimize energy consumption. Optimizing the process parameters can reduce printing time, energy usage, and the overall environmental impact. According to this study, which was conducted with an FFF UltiMaker printer, the following optimized process parameters are recommended for minimizing energy consumption:
  - Adjust the layer height according to the printer's nozzle. For a highly detailed surface finish, a lower layer height is recommended. As a rule of thumb, set the layer height to between 20% and 80% of the printer nozzle's diameter.
  - The infill density directly affects material consumption and the weight of the printed part. Higher infill percentages enhance the strength and mechanical properties of the part, making it suitable for end-use applications. For most visual purpose models, a 20% infill density is commonly used.
  - Different infill pattern geometries have minimal impact on energy and the environment, as observed in the conducted study. However, the concentric infill pattern exhibits the lowest energy values. For prints requiring high ultimate tensile strength, cubic and grid patterns are recommended [13].
  - Follow the recommended temperature guidelines provided by the filament manufacturer (UltiMaker, in this case) for each material. Based on the conducted experiments, the effect of temperature changes on energy and the environment is found to be marginal.
  - Printing speed is inversely correlated with energy consumption. It is advisable to use higher printing speeds to minimize the environmental impact. Start by adjusting the speed according to the manufacturer's guidelines and gradually

increase it in small increments while monitoring print quality to avoid stringing and poor adhesion to the print bed.

- Educational Sustainability Focus: One initiative that aims to promote energy efficiency and environmental sustainability in relation to 3D printing is introducing the concept of sustainability and circular economy to students. By doing so, students will become more aware of the environmental implications associated with their designs and adopt eco-friendly 3D-printing practices. Furthermore, incorporating discussions and workshops focused on sustainability and the environment will encourage students to practice responsible consumption in 3D printing and contribute to a more sustainable future.

To this end, in order to achieve resource efficiency and energy savings and minimize environmental impacts for a sustainable future, the proposed guidelines offer directions and standards for 3DP users in the education sector. These sustainable 3D-printing guidelines can benefit practitioners and 3DP users by promoting environmental consciousness, enhancing learning opportunities, and ensuring the long-term viability of 3DP technology within the educational setting. Therefore, practitioners are able to have a positive impact on their institutions and communities by incorporating sustainability into their practices. The proposed guidelines are generic and can be applied to any printer model and any of the process parameters.

It is important to note that these guidelines and parameters are based on the UltiMaker printer model adopted in this study, and they may require fine-tuning depending on the specific 3D-printing technology, machine model, and the desired print quality. Different printer models and material filaments from other manufacturers may exhibit different behaviors and yield different results. Potential variations in results could include the following:

- Different FFF printer models, such as Prusa, MakerBot, Stratasys Fortus, etc., have different temperature control systems, layer resolutions, extrusion rates, slicing software profiles, and hardware specifications, including extruder type, nozzle size, and build volume. These variations could result in different material consumption and energy usage, and consequently, different environmental impacts.
- There are various 3D-printing technologies like selective laser sintering (SLS), multi-jet fusion (MJF), electron beam melting (EBM), and direct metal laser sintering (DMLS). Tagliaferri et al. [39] compared different additive manufacturing technologies by adopting different 3D-printer models. Their results revealed that the Fortus 450mc 3D printer has a lower production capacity due to its inability to build multiple objects simultaneously. Economically, the authors stated that the raw material cost of fused deposition modeling (FDM) 3D printers was higher compared to that of SLS and MJF machines. FDM technology was the highest contributor to the environmental impact categories, followed by SLS and MJF. Notably, the MFJ machine had lower electricity consumption compared to the others.
- Polymer filament materials can vary from one manufacturer or supplier to another [40]. Although the filaments share the same general category, e.g., ABS, PLA, polyether ether ketone (PEEK), the manufacturing processes and formulations employed by different companies lead to different characteristics, including:
    a. Material composition, where manufacturers use additives and different blends to achieve particular filament material properties
    b. Filament diameter varies slightly between manufacturers. The standard diameter is 1.75 mm or 2.85 mm; however, a few micrometers' variation can affect the print quality and extrusion consistency.
    c. Printing temperature ranges from one filament to another. Manufacturers design filaments with narrow or broad temperature ranges.

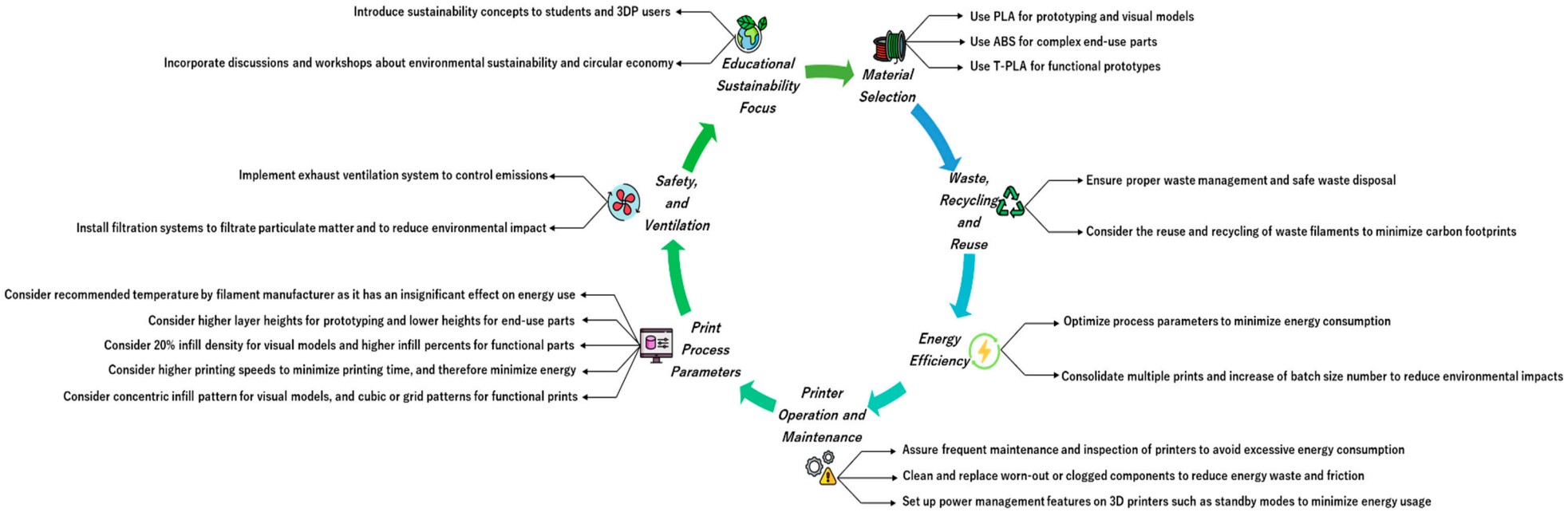


Figure 15. Guidelines for 3D-printing users in education for reducing environmental impacts.

4. Conclusions and Future Work

This paper has assessed the energy consumption and environmental impacts of three thermoplastic polymers, namely PLA, ABS, and T-PLA. The assessment considered five levels of geometric complexity and three levels of various process parameters, including layer height, infill density, infill pattern, speed, and temperature. The influence of each parameter was analyzed, and optimized process parameters were suggested accordingly. Guidelines were provided for 3DP users in schools, universities, and Fab Labs to reduce energy consumption and achieve environmental sustainability. Life-cycle assessment methods, such as ReCiPe and CED, were employed to extract the environmental impact data.

The analysis results indicate that PLA is the most environmentally friendly material, whereas ABS exhibits the highest 3D-printing energy, CO_2 emissions, and human toxicity. The toughening process for PLA requires high energy due to the annealing and heat-treatment processes. However, it is important to note that there are no definitive or determinative guidelines or specific process parameters to follow. The choice of parameters depends on the specific case, taking into account the purpose and specifications of the print and the 3D-printer model. Therefore, spreading sustainability concepts among society and educational institutions is crucial for incorporating environmentally friendly practices when using 3D printers.

Future Work

- The current study has considered a limited range of geometric complexity levels. However, incorporating a more diverse and broader range of geometric shapes and sizes would yield different outcomes and provide a deeper understanding of the energy consumption and environmental impacts of FFF 3D printing.
- A future direction could involve the consideration and comparative analysis of additional filament materials, such as thermoplastic polyurethane (TPU), polyether ether ketone (PEEK), and polyethylene terephthalate glycol (PETG). This would provide comprehensive guidelines and profound insights into sustainable 3D-printing practices.
- In this study, UltiMaker 2+ Connect was adopted to conduct the experiments. Extending this work to a comparative analysis with multiple 3D-printer models using different 3D-printing technologies would lead to more comprehensive and accurate results.
- In this paper, we have proposed guidelines for the education sector to effectively integrate 3D printing. However, expanding the scope of this work considering different 3D-printing application scenarios in various industry sectors, such as the biomedical field, consumer products sector, and manufacturing, would provide useful insights and more specific and practical recommendations for the optimal utilization of 3D printing across various sectors, empowering industries with cutting-edge technologies and fostering innovation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151612319/s1, Table S1: Energy values of all gears when changing layer height; Table S2: Energy values of all gears when changing infill density. Table S3: Energy values of all gears when changing infill pattern. Table S4: Energy values of all gears when changing printing temperature. Table S5. Energy values of all gears when changing printing speed.

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