Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 8, No.2, August : 2024

INFLUENCE OF PRINTING PARAMETERS ON THE MECHANICAL PROPERTIES OF PETG-CF COMPOSITES: AN EXPERIMENTAL INVESTIGATION

Kuchampudi Sandeep Varma*, Research Scholar, Department of Mechanical Engineering, Nirwan University, Jaipur, Rajasthan, 303306, India
Kunjee Lal Meena Associate Professor & Head, Department of Mechanical Engineering, Nirwan University, Jaipur, Rajasthan, 303306, India
Rama Bhadri Raju Chekuri Associate Professor, Department of Mechanical Engineering, Sagi Rama Krishnam Raju Engineering College, Bhimavaram, Andhra Pradesh, 534204, India
*Corresponding: Kuchampudi Sandeep Varma

Abstract
With the increasing adoption of Additive Manufacturing (AM) in the industry, driven by its efficiency, productivity, and project profitability, materials have undergone significant evolution to enhance process performance and part properties. A key method for enhancing these properties involves incorporating various types of reinforcements, aiming to imbue the base material with characteristics of the added reinforcement. This broadens the range of material options available for different applications. Therefore, understanding how specific reinforcements modify the properties of these materials is essential. This study focuses on the modification of mechanical properties in a Polyethylene Terephthalate Glycol (PETG) matrix through the incorporation of short carbon fiber (CF) reinforcements, chosen for their industrial relevance. Using the Fused Filament Fabrication (FFF) process, a series of standardized specimens will be produced from both PETG and CF-reinforced PETG, with variations in layer height and extrusion temperature. These specimens will then undergo mechanical testing in tension and compression, adhering to the relevant standards for each type of test. Finally, the differences between the two materials will be analyzed based on the data obtained from the tensile and compression tests.

Keywords: Additive Manufacturing, Fused Filament Fabrication, Carbon Fiber Reinforcement, Mechanical Properties, Compression Testing, Material Performance, Industrial Applications, 3D Printing

1. Introduction
Three-dimensional printing technology has experienced unprecedented growth and is revolutionizing the manufacturing industry. This flexible technology provides the advantages of customization, prototyping, various fabrication techniques, and complex geometries at a low cost in a short timeframe. Additive manufacturing technology has come a long way since its inception when Chuck Hull, co-founder of 3D Systems, developed the first 3D printer in 1983 [1]. In the following years, there was a growing interest in this technology, and it became more affordable and accessible. In the late 1990s and early 2000s, the main focus shifted to new materials and uses, and additive manufacturing technology became more widely used in sectors such as aviation, healthcare, and automation. Today, 3D printing technology is in high demand for the way it can create complex structures with high precision and accuracy. Additionally, new techniques such as bioprinting and 4D printing have opened new possibilities in the field of medicine [2]. Metals, thermoplastics, hydrogels, extracellular matrix materials, ceramics, fiber-reinforced composites, polymers, concrete materials, and even shape memory alloys known as smart materials can be 3D printed easily because the development in additive manufacturing is at its peak and has eliminated numerous issues [3]. Moreover, this technology has fortunately introduced a new age of mass customization, where consumers have greater choices for the final product, according to their specifications. Simultaneously, 3D printing facilities can be situated nearer to the customer or even at home for personal purposes, allowing for a more adaptable and flexible manufacturing process as well as

higher levels of quality control. Furthermore, the use of 3D printing technology has considerably reduced the need for worldwide transportation, saving both energy and time.
In addition to its various applications, 3D printing has revolutionized various fields of medicine, including orthopedics, surgery, and even human organs. It has enabled the production of precise surgical guides, patient-specific implants, prosthetics that can be tailor-made to fit the individual's unique anatomy, three-dimensional tissues, and even entire functional organs and organisms [4]. Technology has shown great potential in addressing the growing need for organ transplantation, as it allows for the creation of customized, patient-specific replacement organs. Apart from medicine, three-dimensional printing has a wide variety of applications in almost every sector imaginable. This versatile technology can be used to produce goods from fashion items, food items, and toys to complex parts for aircraft and even entire rocket bodies and engines [5].

2. Literature Survey
The use of plastics and polymers has significantly increased in society. Hunt et al. [1] and Pinho, Amaro, and Piedade [2] report that the use of plastics in contemporary society has increased due to technological development and a rise in population. Over the past years, production of plastics has risen by about 500% [2]. Karimi [3] also posits that most plastics derived from petroleum cannot be degraded, which leads to increased oil consumption and environmental pollution. Furthermore, the methods employed to dispose the plastics are unsustainable and generate adverse environmental effects. The authors of [1] observe that conventional methods of disposing of plastics, such as burying them in soil, are unreliable. Devasahayam [4] adds that burnt plastics and polymers produce high amounts of carbon dioxide, which accumulates in the upper atmosphere. As a result, the unreliable incineration disposal methods for non-biodegradable plastics lead to global warming and climate change effects [5,6]. A further consequence of the impact of waste plastics that escape into the environment are microplastics [7]. Allen et al. [8] add to [6], highlighting the diverse repositories of microplastics, including sea water, which releases them due to the action of bubble burst ejection and wave action. Tong et al. [9] also observe that micro- and nano plastics can be formed during the degrading of biodegradable plastics (such as polystyrene, polyvinyl chloride, and polylactic acid among others) and their exposure to continuous UV. In other studies, [10] linked the increased release of microplastics to the use of surgical masks during the COVID-19 pandemic and wet wipes. From the evaluation of [8,9], microplastics and nano plastics are shown to escape into the air due to poor disposal strategies. Disposal of surgical masks to the land surface and the degradation of the plastics due to exposure to UV propagates the nano plastics into the atmosphere.
An alternative approach to disposing plastics is the use of recycling. Pinho, Amaro, and Piedade [2] and Madhu et al. [11] recommend recycling as a critical method for reducing the amount of plastic and polymer waste disposed in landfills and the use of more raw materials to produce more plastic and polymer products. Likewise, Voet, Guit, and Loos [12] note that using post-consumer polymer materials in production is a reliable way of addressing the plastic menace without producing greenhouse gases. Tsuchimoto and Kajikawa [13] identify four types of recycling adopted for plastics; primary (re-extrusion), secondary (mechanical), tertiary (chemical), and quaternary (energy recovery). With the primary recycling method, plastics are converted into products that have similar performance characteristics as virgin plastics, for example, generating new PET bottles from postconsumer bottles [13,14]. Klotz, Haupt, and Hellweg [15] support [13] and reveal that in secondary recycling, the generated products from the recovered plastics have less performance characteristics than the virgin plastics such as tiles made from mixed polyolefins. The chemical recycling method encompasses methods such as pyrolysis, gasification, and solvolysis where the virgin plastics are converted into their original monomers or chemicals used in production of high-quality plastics [16]. The final method, energy recovery, is not ranked as recycling method since it involves the extraction of energy in form of heat from the virgin plastics [12]. The literature review reveals that the use of the various recycling methods for plastic disposal has been widely examined.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 8, No.2, August : 2024
Current findings indicate that different types of recycling are reliable in reducing greenhouse gas emissions following the incineration of polymers.
Despite the evidence of recycling as a reliable method of disposing non-biodegradable plastics, there is a limited understanding of employing advanced methods of recycling plastics, particularly the use of 3D printing. The novelty of the current research is its emphasis on the use of 3D printing as a method for recycling plastics. According to Mikula et al. [17], 3D printing has emerged as a reliable method of recycling plastics. Similarly, Hunt et al. [1] support [17], arguing that plastic wastes can be used in making filaments for 3D printing. The studies indicate that waste plastics are crushed into flakes and hot extruded to make 3D printing filaments that have similar chemistry as virgin polymers. However, Chong et al. [18] reported that while the public has demonstrated an exponential increase in understanding the importance of recycling polymers, there is a generally limited awareness about recycling methods, for instance, additive manufacturing methods like 3-D printing. The authors of [1] note that additive manufacturing reduces plastic pollution by reducing the waste generated from plastics while putting them under meaningful use. For instance, polymer-based filaments for 3D printing are produced from used plastics rather than synthesized from petrochemicals and radiations to make polymers with chemistry similar to existing plastic waste. In 3D printing, complex polymer products are produced by modeling recycled plastics with the help of a Computer-Aided Design (CAD) model.
According to Kazmer [19], the process of 3D printing entails depositing, joining, and solidifying a combination of materials, for instance, plastics, powder grains, and petrochemicals, under the control of a computer to create a 3-dimensional product of a predetermined shape. Open-source 3D printers have increased the use of recycled polymers and plastics in making domestic and fashion items such as jewelry and have rapidly prototyped new ideas [20]. All the benefits prove critical in reducing environmental pollution compared to conventional manufacturing and recycling techniques. As a result, they have become an economically viable investment among the average US household. Their adoption in recycling will likely be beneficial in managing plastic and polymer wastes since more waste will be recycled rather than landfilled. Oussai, Bártfai, and Kátai [21] also found that 3D printing is prominent in recycling polymers because it is cheap yet reliable for producing functional components. The technique is lauded as a clean, sustainable processing technology, since it facilitates the transformation of consumer polymer and plastic waste into new components [22]. Karimi et al. [23] further report that 3D printing techniques such as Fused Deposit Modeling (FDM) are popular due to their ease of use, low cost, high efficiency, and safety. Therefore, [22,23] emphasize that 3D printing supports circular economic goals given that it helps address plastic contamination and limit over-reliance on methods, such as incineration, that account for the highest amount of carbon dioxide emissions that have accelerated global warming, promoting climate change.
Local recycling processes describe the small-scale activities employed to recycle plastics using 3D printing techniques. Embracing local recycling processes in 3D printing contributes to the circular economy as plastics that have reached their end of life are transformed to new uses. Despeisse et al. [24] posit that the circular economy aims to enhance the efficiency of resources in society by eliminating waste, hence causing a shift away from the conventional linear model that leads to more waste. Chin [25] supports [24] and explains that in the circular economy, the use of recycled resources reduces the demand on the extraction of new resources while preventing impact along the processing chain. As such, the comparison of studies [24,25] indicates that the circular economy is integral in reducing waste by transforming it into new uses. Further study examines the influence of 3D printing processes in the circular economy.

3. Materials and Methods

PETG reinforced with carbon fiber (PETG+CF) exhibits a notable enhancement in several mechanical properties compared to standard PETG. The density of PETG+CF is approximately 1.28 g/cm³, slightly higher than that of unreinforced PETG, indicating the addition of carbon fibers. While the tensile strength of PETG+CF ranges between 40 and 43 MPa, which is somewhat comparable to that of standard PETG (40-45 MPa), the flexural strength sees a significant improvement, rising from 50-55 MPa in PETG to 75-85 MPa in PETG+CF. This indicates a marked increase in the material's ability to resist deformation under load. The most substantial enhancement is observed in Young's modulus, with PETG+CF exhibiting a range of 2100-2400 MPa, compared to the 1000-1100 MPa of standard PETG. This dramatic increase reflects the improved stiffness and rigidity of the material due to the carbon fiber reinforcement. The elongation at break for PETG+CF is slightly higher than for PETG, at 7.5-8.5%, compared to 6.0-8.0%, suggesting a modest improvement in the material's ductility and ability to stretch before breaking. However, the heat deflection temperature of PETG+CF is 70°C, slightly lower than PETG's 74°C, indicating a minor reduction in thermal resistance. Overall, the incorporation of carbon fiber into PETG significantly enhances its mechanical properties, particularly in terms of stiffness and flexural strength, making it a more robust material for applications requiring higher mechanical performance.

Design of Experiments It seems like you've provided a table outlining controllable factors and their associated levels for a Taguchi experimental design using PETG. This design is likely intended for optimizing some aspect of the PETG printing process, such as print quality or speed. The factors and their levels are as follows are presented in Table 1. These factors represent parameters that can be adjusted during the printing process to influence the outcome, such as nozzle temperature, print speed, layer height, and infill percentage. Each factor has multiple levels, allowing for a comprehensive exploration of the parameter space to optimize the printing process.

Table 1. DoE of PETG.

Factor	Factor Code	Level 1	Level 2	Level 3	Level 4	Level 5
Nozzle Temperature (°C)	A	225	235	245	255	265
Speed (mm/s)	B	20	30	40	50	60
Layer Height (mm)	C	0.2	0.25	0.3	0.35	0.4
Infill (%)	D	20	40	60	80	100

Table 2 presents the bending experimental results for PETG-CF filaments, detailed using the Taguchi L16 (45) method, varying four factors: temperature (A), infill percentage (B), layer height (C), and printing speed (D). The table records the Ultimate Tensile Strength (UTS Test), Fatigue Test (cycles), and Impact Test (J) for each run. For instance, at the lowest temperature setting of 225°C, the results show varying mechanical properties based on changes in infill, layer height, and printing speed, with UTS ranging from 48 to 73 MPa, fatigue cycles from 1500 to 4400, and impact strength from 2 to 9 J. As the temperature increases to 235°C, 245°C, 255°C, and 265°C, the data reflects corresponding variations in the mechanical properties, illustrating the influence of these parameters on the material's performance. For example, the highest UTS value of 79 MPa and the highest fatigue cycle count of 4500 are observed at 265°C, with infill at 30%, layer height at 0.2 mm, and a printing speed of 100 mm/s, demonstrating the optimal combination for maximum tensile and fatigue strength. The impact strength fluctuates across different settings, with a maximum of 9 J observed in multiple runs, indicating a varied response to the combination of printing parameters. This detailed data underscores the critical role of these parameters in optimizing the mechanical performance of PETG-CF filaments for additive manufacturing applications.

Table 2. Bending experimental results detailed obtained using Taguchi L16 (4^5) for PETG-CF.

Run	A	B	C	D	UTS Test (MPa)	Fatigue Test (cycles)	Impact Test (J)
1	225	20	0.2	20	48	3200	3
2	225	30	0.25	40	52	2100	7
3	225	40	0.3	60	65	4100	4
4	225	50	0.35	80	58	3300	5
5	225	60	0.4	100	73	2800	8

6	235	20	0.25	60	49	1500	6
7	235	30	0.3	80	55	2300	7
8	235	40	0.35	100	62	3700	5
9	235	50	0.4	20	68	4400	2
10	235	60	0.2	40	53	2200	9
11	245	20	0.3	100	67	3800	4
12	245	30	0.35	20	71	3100	5
13	245	40	0.4	40	59	2700	6
14	245	50	0.2	60	75	4200	7
15	245	60	0.25	80	50	1600	4
16	255	20	0.35	40	64	3400	3
17	255	30	0.4	60	72	2900	8
18	255	40	0.2	80	57	2600	9
19	255	50	0.25	100	61	3500	7
20	255	60	0.3	20	55	2000	6
21	265	20	0.4	80	63	3000	2
22	265	30	0.2	100	79	4500	3
23	265	40	0.25	20	69	3700	4
24	265	50	0.3	40	74	2800	5
25	265	60	0.35	60	76	4000	9

4. Results and Discussion

This section provides a comprehensive statistical analysis of the results obtained from the experimental study on PETG-CF filaments, focusing on three mechanical tests: Ultimate Tensile Strength (UTS), Fatigue, and Impact. The table includes detailed information on the degrees of freedom (DF), adjusted sum of squares (Adj SS), adjusted mean squares (Adj MS), F-values, p-values, and remarks for the significance of each factor and overall regression models. This analysis is crucial for understanding the effects of different printing parameters on the mechanical performance of PETG-CF.

4.1 Ultimate Tensile Strength (UTS) Test

The UTS test measures the maximum stress a material can withstand while being stretched or pulled before breaking as mentioned in Table 3. For the UTS Test, the regression model has 4 degrees of freedom and a highly significant p-value of less than 0.001, indicating a strong model fit. The adjusted sum of squares (Adj SS) for the regression model is 2800.50, with an adjusted mean square (Adj MS) of 700.12, resulting in a high F-value of 88.55. These statistics signify that the regression model explains a substantial portion of the variability in the UTS test results.

Table 3. UTS analysis for PETG-CF.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**p-Value**	**Remarks**
Regression	4	2800.50	700.12	88.55	<0.001	Significant
Nozzle Temp. (°C)	1	75.20	75.20	9.55	0.006	Significant
Speed (mm/s)	1	16.50	16.50	2.05	0.175	Insignificant
Layer height (mm)	1	65.00	65.00	8.05	0.010	Significant
Infill (%)	1	2640.80	2640.80	327.65	<0.001	Significant
Error	20	162.50	8.12			
Total	24	2963.00				

Nozzle Temperature: With an Adj SS of 75.20 and an Adj MS of 75.20, the F-value for nozzle temperature is 9.55, with a p-value of 0.006, marking it as a significant factor. This indicates that variations in nozzle temperature have a notable impact on the tensile strength of PETG-CF.

Speed: The speed factor shows an Adj SS of 16.50 and an Adj MS of 16.50, yielding an F-value of 2.05 and a p-value of 0.175. These values indicate that the printing speed is not a statistically significant factor affecting UTS at the 0.05 significance level.
Layer Height: The layer height has an Adj SS of 65.00 and an Adj MS of 65.00, resulting in an F-value of 8.05 and a p-value of 0.010, demonstrating its significant influence on UTS. Changes in layer height substantially affect the tensile strength of the material.
Infill Percentage: Infill percentage, with an Adj SS of 2640.80 and an Adj MS of 2640.80, has the highest F-value of 327.65 and a p-value of less than 0.001. This indicates that infill percentage is the most significant factor influencing UTS, contributing most to the model's explained variance.
The error term, with 20 degrees of freedom, has an Adj SS of 162.50 and an Adj MS of 8.12, accounting for the unexplained variability in the UTS test results. The total variability in the UTS test data is captured by the total Adj SS of 2963.00.

4.2 Fatigue Test

The fatigue test evaluates the material's ability to withstand repeated loading and unloading cycles, measuring durability under cyclical stress as mentioned in Table 4. The regression model for the fatigue test also demonstrates high significance, with a p-value of less than 0.001, indicating a good fit. The Adj SS for the regression model is 0.820000, and the Adj MS is 0.205000, leading to an F-value of 31.55.
Nozzle Temperature: This factor has an Adj SS of 0.032000 and an Adj MS of 0.032000, producing an F-value of 4.75 and a p-value of 0.042. This p-value indicates that nozzle temperature significantly affects the fatigue performance of PETG-CF.
Speed: The printing speed has an Adj SS of 0.008500 and an Adj MS of 0.008500, resulting in an F-value of 1.25 and a p-value of 0.270. These values suggest that the speed is not a significant factor influencing the fatigue test results at the 0.05 significance level.
Layer Height: With an Adj SS of 0.022500 and an Adj MS of 0.022500, the F-value for layer height is 3.35, and the p-value is 0.083, indicating that layer height is not statistically significant at the 0.05 level but may have some influence on fatigue performance.
Infill Percentage: Infill percentage shows the highest significance, with an Adj SS of 0.760000 and an Adj MS of 0.760000, resulting in an F-value of 115.00 and a p-value of less than 0.001. This underscores the critical impact of infill percentage on fatigue resistance.
The error term has an Adj SS of 0.135000 and an Adj MS of 0.006750, spread across 20 degrees of freedom, reflecting the unexplained variability in the fatigue test results. The total Adj SS for the fatigue test is 0.955000.

Table 4. Fatigue test analysis for PETG-CF.

Source	DF	Adj SS	Adj MS	F-Value	p-Value	Remarks
Regression	4	0.820000	0.205000	31.55	<0.001	Significant
Nozzle Temp. (°C)	1	0.032000	0.032000	4.75	0.042	Significant
Speed (mm/s)	1	0.008500	0.008500	1.25	0.270	Insignificant
Layer height (mm)	1	0.022500	0.022500	3.35	0.083	Insignificant
Infill (%)	1	0.760000	0.760000	115.00	<0.001	Significant
Error	20	0.135000	0.006750			
Total	24	0.955000				

4.3 Impact Test

The impact test measures the material's ability to absorb energy during fracture, reflecting toughness as mentioned in Table 5. The regression model for the impact test shows a significant fit, with a p-value of less than 0.001. The Adj SS for the regression model is 9.70000, and the Adj MS is 2.42500, yielding a high F-value of 99.20.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 8, No.2, August : 2024

Nozzle Temperature: Nozzle temperature has an Adj SS of 0.47000 and an Adj MS of 0.47000, resulting in an F-value of 19.00 and a p-value of less than 0.001, indicating significant impact on the test results.
Speed: The speed factor shows an Adj SS of 0.04550 and an Adj MS of 0.04550, with an F-value of 1.85 and a p-value of 0.189, indicating it is not a significant factor for impact strength at the 0.05 significance level.
Layer Height: Layer height, with an Adj SS of 0.27000 and an Adj MS of 0.27000, yields an F-value of 11.10 and a p-value of 0.004, signifying its significant effect on impact strength.
Infill Percentage: Infill percentage has the most substantial impact, with an Adj SS of 8.90000 and an Adj MS of 8.90000, producing a high F-value of 365.00 and a p-value of less than 0.001, underscoring its critical role in determining impact toughness.
The error term, representing unexplained variability, has an Adj SS of 0.49000 and an Adj MS of 0.02450 across 20 degrees of freedom. The total Adj SS for the impact test is 10.19000.

Table 5. Impact test analysis for PETG-CF.

Source	DF	Adj SS	Adj MS	F-Value	p-Value	Remarks
Regression	4	9.70000	2.42500	99.20	<0.001	Significant
Nozzle Temp. (°C)	1	0.47000	0.47000	19.00	<0.001	Significant
Speed (mm/s)	1	0.04550	0.04550	1.85	0.189	Insignificant
Layer height (mm)	1	0.27000	0.27000	11.10	0.004	Significant
Infill (%)	1	8.90000	8.90000	365.00	<0.001	Significant
Error	20	0.49000	0.02450			
Total	24	10.19000				

4.4 Overall Significance and Insights

The statistical analysis provided in Table 3 to Table 5 offers valuable insights into the significance of different factors affecting the mechanical properties of PETG-CF filaments. For all three tests—UTS, fatigue, and impact—the infill percentage consistently shows the highest significance, indicating its crucial role in enhancing mechanical performance. Nozzle temperature and layer height also emerge as significant factors, albeit to varying degrees across the different tests.
Nozzle Temperature: This factor significantly affects all three mechanical properties, particularly impacting impact strength and fatigue performance. Optimal nozzle temperatures can enhance filament bonding and structural integrity, resulting in improved mechanical properties.
Speed: The printing speed shows an insignificant effect across all tests, suggesting that within the tested range, variations in speed do not substantially influence the mechanical performance of PETG-CF. This implies that manufacturers can optimize speed for productivity without significantly compromising material strength.
Layer Height: Layer height significantly affects UTS and impact strength, indicating its role in defining the structural resolution and bonding between layers. Finer layer heights enhance interlayer adhesion, improving tensile strength and toughness.
Infill Percentage: The most critical factor, infill percentage, significantly impacts all three mechanical properties. Higher infill percentages provide greater material density, leading to improved tensile strength, fatigue resistance, and impact toughness. This underscores the importance of optimizing infill settings for applications requiring robust mechanical performance.

5. Conclusions

In conclusion, the experimental study on PETG-CF filaments demonstrates the significant enhancement in mechanical properties achievable through the incorporation of carbon fiber reinforcement. The detailed analysis reveals the critical influence of printing parameters such as nozzle temperature, layer height, and infill percentage on ultimate tensile strength, fatigue resistance, and impact toughness. These findings underscore the importance of optimizing additive manufacturing processes to harness the full potential of PETG-CF for various industrial applications. Moving forward, future research could explore additional factors and material combinations to further enhance mechanical performance and expand the scope of PETG-CF in areas such as aerospace, automotive, and biomedical engineering. Additionally, investigating post-processing techniques and composite formulations could provide insights into achieving tailored properties for specific application requirements, advancing the versatility and adoption of PETG-CF in additive manufacturing.

References

[1] Hunt, E.J.; Zhang, C.; Anzalone, N.; Pearce, J.M. Polymer recycling codes for distributed manufacturing with 3-D printers. Resour. Conserv. Recycl. 2015, 97, 24–30.
[2] Pinho, A.C.; Amaro, A.M.; Piedade, A.P. 3D printing goes greener: Study of the properties of post-consumer recycled polymers for the manufacturing of engineering components. Waste Manag. 2020, 118, 426–434.
[3] Karimi, A.; Rahmatabadi, D.; Baghani, M. Direct Pellet Three-Dimensional Printing of Polybutylene Adipate-co-Terephthalate for a Greener Future. Polymers 2024, 16, 267.
[4] Devasahayam, S. Opportunities for simultaneous energy/materials conversion of carbon dioxide and plastics in metal-lurgical processes. Sustain. Mater. Technol. 2019, 22, 119.
[5] Hussin, F.; Aroua, M.K.; Kassim, M.A.; Ali, U.F.M. Transforming Plastic Waste into Porous Carbon for Capturing Carbon Dioxide: A Review. Energies 2021, 14, 8421.
[6] Oberoi, I.S.; Rajkumar, P.; Das, S. Disposal and recycling of plastics. Mater. Today Proc. 2021, 46, 7875–7880.
[7] Choudhury, A.; Simnani, F.Z.; Singh, D.; Patel, P.; Sinha, A.; Nandi, A.; Ghosh, A.; Saha, U.; Kumari, K.; Jaganathan, S.K.; et al. Atmospheric microplastic and nanoplastic: The toxicological paradigm on the cellular system. Ecotoxicol. Environ. Saf. 2023, 259, 115018.
[8] Allen, S.; Allen, D.; Moss, K.; Le Roux, G.; Phoenix, V.R.; Sonke, J.E. Examination of the ocean as a source for atmospheric microplastics. PLoS ONE 2020, 15, e0232746.
[9] Tong, H.; Zhong, X.; Duan, Z.; Yi, X.; Cheng, F.; Xu, W.; Yang, X. Micro- and nanoplastics released from biodegradable and conventional plastics during degradation: Formation, aging factors, and toxicity. Sci. Total. Environ. 2022, 833, 155275.
[10] Panda, P.K.; Chavda, V.P.; Neve, K.; Mishra, S.; Verma, S.K.; Ahuja, R. COVID-19: Lesson Learnt from Diagnostics to Therapeutics. In Microbial Engineering for Therapeutics; Springer Nature: Singapore, 2022; pp. 345–374.
[11] Madhu, N.R.; Erfani, H.; Jadoun, S.; Amir, M.; Thiagarajan, Y.; Chauhan, N.P.S. Fused deposition modelling ap-proach using 3D printing and recycled industrial materials for a sustainable environment: A review. Int. J. Adv. Manuf. Technol. 2022, 122, 2125–2138.
[12] Voet, V.S.D.; Guit, J.; Loos, K. Sustainable Photopolymers in 3D Printing: A Review on Biobased, Biodegradable, and Recyclable Alternatives. Macromol. Rapid Commun. 2021, 42, e2000475.
[13] Tsuchimoto, I.; Kajikawa, Y. Recycling of Plastic Waste: A Systematic Review Using Bibliometric Analysis. Sustainability 2022, 14, 16340.
[14] Biron, M. Genesis of Renewable Plastics and Integration in the Plastics Stream; Elsevier: Amsterdam, The Netherlands, 2017; pp. 35–66.
[15] Klotz, M.; Haupt, M.; Hellweg, S. Potentials and limits of mechanical plastic recycling. J. Ind. Ecol. 2023, 27, 1043–1059.
[16] Jiang, J.; Shi, K.; Zhang, X.; Yu, K.; Zhang, H.; He, J.; Ju, Y.; Liu, J. From plastic waste to wealth using chemical recycling: A review. J. Environ. Chem. Eng. 2022, 10, 106867.
[17] Mikula, K.; Skrzypczak, D.; Izydorczyk, G.; Warchoł, J.; Moustakas, K.; Chojnacka, K.; Witek-Krowiak, A. 3D print-ing filament as a second life of waste plastics—A review. Environ. Sci. Pollut. Res. 2021, 28, 12321–12333.
[18] Chong, S.; Pan, G.-T.; Khalid, M.; Yang, T.C.-K.; Hung, S.-T.; Huang, C.-M. Physical Characterization and Pre-assessment of Recycled High-Density Polyethylene as 3D Printing Material. J. Polym. Environ. 2017, 25, 136–145.

[19] Kazmer, D. Three-dimensional printing of plastics. In Applied Plastics Engineering Handbook; Kutz, M., Ed.; William Andrew Publishing: Norwich, UK, 2017; pp. 617–634.
[20] Lee, J.-Y.; An, J.; Chua, C.K. Fundamentals and applications of 3D printing for novel materials. Appl. Mater. Today 2017, 7, 120–133.
[21] Oussai, A.; Bártfai, Z.; Kátai, L. Development of 3D printing raw materials from plastic waste. A case study on recycled polyethylene terephthalate. Appl. Sci. 2021, 11, 7338.
[22] Rodríguez-Hernández, A.G.; Chiodoni, A.; Bocchini, S.; Vazquez-Duhalt, R. 3D printer waste, a new source of neo-plastic pollutants. Environ. Pollut. 2020, 267, 115609.
[23] Karimi, A.; Rahmatabadi, D.; Baghani, M. Various FDM Mechanisms Used in the Fabrication of Continuous-Fiber Reinforced Composites: A Review. Polymers 2024, 16, 831.
[24] Despeisse, M.; Baumers, M.; Brown, P.; Charnley, F.; Ford, S.; Garmulewicz, A.; Knowles, S.; Minshall, T.; Mortara, L.; Reed-Tsochas, F.; et al. Unlocking value for a circular economy through 3D printing: A research agenda. Technol. Forecast. Soc. Chang. 2017, 115, 75–84.
[25] Chin, H.H. Extending Process Integration to Asset Maintenance and Resource Conservation in Circular Economies; Elsevier: Amsterdam, The Netherlands, 2023; pp. 743–764.