

A Comparative Analysis of the Climate Impact Assessment of 3D Printing Materials

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Abstract. 3D printing, technically called additive manufacturing, has high hopes of being material-efficient toward sustainable production potential. The printing material significantly changes the total environmental effect of the process itself. This study presents a life cycle assessment (LCA) comparison based on three common thermoplastic filaments: Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS) and Polyethylene Terephthalate Glycol (PETG). The analysis covers four stages of the life cycle: raw material extraction, manufacturing, usage, and end-of-life recycling, with openLCA and using the ecoinvent 3.10 database support. Impacts were evaluated on major fronts like Global Warming Potential (GWP), Acidification, Eutrophication Potential, Ozone Layer Depletion, Photochemical Ozone Creation Potential, plus human toxicity using the Centrum voor Milieukunde Leiden (CML) method in functional terms by applying a 125 cm³ 3D printed cube as the unit for fair comparison. PLA proves to be the least environmentally impactful material since it is derived from renewable sources, consumes less energy, and partially biodegrades. In most categories, ABS proves to be the most impactful material, as it is also derived from fossil resources and requires more energy during recycling. PETG proves to be better than ABS but does not prove to be as sustainable as PLA, particularly in climate change and acidification impacts. This finding can lead to environmental sustainability through increased consumption of PLA material in additive manufacturing, together with improved agricultural practices and recycling methods.

1 INTRODUCTION

The primary emphasis in achieving Sustainable Development Goals (SDGs) 9 and 12 is on creating robust infrastructure, encouraging sustainable industrial development, nurturing innovation and adopting responsible practices for production and consumption [1]. In this framework, sustainable manufacturing has surfaced as an essential strategy focused on reducing environmental harm by cutting down on energy and resource use during the production process [2]. The Life Cycle Assessment (LCA) method takes into account all

inputs, such as raw materials and energy, along with outputs like waste and emissions produced at each phase of the product's life [3].

The swift advancement of additive manufacturing (AM), commonly referred to as 3D printing, signifies a major shift within the framework of Industry 4.0. Unlike traditional manufacturing, which involves removing material, AM creates objects by layering materials. Typically, this process utilizes thermoplastic filaments that are guided by digital CAD models. Various AM techniques such as fused deposition modeling (FDM), binder jetting, powder bed fusion, material extrusion and sheet lamination have emerged, finding applications across diverse industries. AM now facilitates rapid prototyping, custom product creation and open-source design, influencing sectors such as electronics, automotive, food production, healthcare, architecture, fashion and aerospace.

Beyond enabling flexible design, 3D printing streamlines supply chains and assembly processes, minimizes the requirement for specialized tools, increases product longevity and fosters greater creative opportunities. To mitigate the environmental effects of AM, it is crucial to integrate sustainability principles into these processes as they gain traction.

PLA, ABS and PETG are some of the thermoplastic filaments utilized in Fused Deposition Modeling (FDM), which is a widely used 3D printing technique [7]. These materials pose significant environmental hazards if not disposed off correctly, like through incineration or landfilling. In addition, recycling thermoplastics demands a considerable amount of energy for material reprocessing, impacting the environmental footprint of the entire process. Therefore, selecting the appropriate type of filament is crucial for the sustainability of the 3D printing supply chain [8].

This study conducted a comprehensive quantitative analysis of the environmental impacts associated with 3D printed products made from three popular FDM filaments: ABS, PLA, and PETG. The results are expected to aid in making informed decisions regarding filament selection that promote more sustainable additive manufacturing practices. This research provides an extensive cradle-to-grave evaluation of FDM materials (PLA, ABS, and PETG), employing the CML impact methodology specifically tailored to the context of Indian manufacturing. In contrast, previous studies have focused on individual 3D printing materials or have compared specific environmental categories.

The innovation is evident in several ways: (i) It merges records from the ecoinvent database (focusing on raw material extraction) with experimental data on energy consumption during the manufacturing phase, obtained through smart metering, to ensure precision; (ii) It applies the CML framework across six key environmental impact categories climate change, acidification, eutrophication, ozone depletion, photochemical oxidant formation and human toxicity to enable a thorough comparison that goes beyond single-indicator assessments; (iii) It considers the energy consumption associated with recycling specific materials (which varies from 10 to 27 MJ/kg) through a detailed process analysis, addressing the often overlooked end-of-life phase in additive manufacturing studies; and (iv) It establishes a standardized functional unit (a 125 cm³ cube with a 30% infill density) to reduce variability found in earlier studies. This comprehensive method facilitates evidence-based material selection for sustainable additive manufacturing in resource-constrained industrial environments.

The extent of this advantage differs based on the scale and application, although AM often shows reduced environmental impacts compared to traditional methods. This benefit is not as significant in large-scale production, like the automotive and construction sectors [10], [11]. Redesigning products and introducing cyber-physical systems have proven to be effective methods for enhancing sustainability [13], [3]. Additionally, adjusting key printing parameters such as fill density, layer height, printing speed and temperature can help minimize environmental impacts [14-15]. The overall environmental impact of additive manufacturing processes is also greatly affected by the materials utilized and the subsequent recycling stage of the product.

3 LIFE CYCLE ASSESSMENT

In this study, the LCA method was employed to evaluate the environmental impacts of 3D printed products made from PLA, PETG and ABS. The assessment was conducted in accordance with the guidelines outlined in the ISO 14040 standards. The main impact indicators for this evaluation were material and energy consumption [9]. These parameters were determined at each life cycle stage through experimental measurements or by sourcing relevant data from existing databases.

3.1 Goal and scope definition

This study aims to evaluate and compare the environmental impacts of three commonly used 3D printing materials PLA, PETG and ABS over four key stages of their life cycle: raw material extraction, manufacturing, usage and recycling. As illustrated in Figure 1, a cube with a volume of 125 cm³ was selected as the functional unit for this analysis. The focus of this assessment is limited to the environmental effects related to the consumption of materials and electricity throughout the product's life cycle.

The majority of India's electricity is derived from non-renewable sources, with coal-fired thermal power plants contributing 75.9% of the overall output. In 2020, renewable sources provided 17.1% of the electricity, while gas and oil accounted for 3.8%, and nuclear energy made up 3.2%, as reported by the International Energy Agency [18].

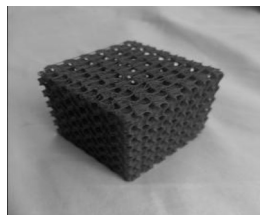


Figure 1. Cube

3.2 System Boundaries

The system boundaries for the various life cycle phases are considered such as raw material extraction, Manufacturing, use phase and recycling phase. All procedures necessary to extract PLA, ABS and PETG from their natural sources and transform them into forms appropriate for 3D printing are included in the raw material extraction phase. The PrusaSlicer application is utilized to prepare the CAD model for the manufacturing phase, with an infill density set at 30%. Once the model has been sliced, the software provides an estimate of the material required for printing. After the G-code is uploaded, the 3D printer self-calibrates, adjusts its temperature and begins the printing process using FDM technology.

It's important to note that the system boundaries exclude the impacts of the 3D printer's actual production, transportation and disposal. However, the LCA consider the energy and materials utilized throughout the printing process.

3.3 Life Cycle Inventory

Data for each step of the life cycle assessment (LCA) were derived either from experimental research or the life cycle inventory database. Table 2 presents the inventory data utilized to assess the environmental impact of PLA, ABS, and PETG filament materials during the manufacturing phase, while Table 1 outlines the printing parameters, including a 30% infill and a layer height of 0.2 mm. Experimental data for the manufacturing phase were collected by 3D printing a cube model [20]. Given that the printed item is passive, there is no energy consumption or emissions generated during its usage.

Table 1. Printing parameters for different filament materials [19]

Materials	Extruder Temperature (°C)	Bed Temperature (°C)
PLA	215	60
ABS	255	110
PETG	230	85

3.3.1 Energy Consumption Calculation during the Recycling Phase

The steps of recycling of the 3D printing materials include four stages, i.e. (i) Collection and Sorting, (ii) Cleaning and Washing, (iii) Shredding or Granulating and (iv) Melting and Extrusion. Each stage of the recycling process needed energy to process the materials. The energy consumption ranges for all three materials at different stages are summarised in Table 2.

Table 2: Energy Consumption Range for Different Stage of Recycling [8, 10,17]

Stages	Materials		
	PLA	ABS	PETG
Collection and Sorting	0.5-1 MJ/kg	0.5-1 MJ/kg	0.5-1 MJ/kg
Cleaning and Washing	1 to 2 MJ/kg	1 to 2 MJ/kg	1 to 2 MJ/kg
Shredding or Granulating	0.5-1 MJ/kg	0.5-1 MJ/kg	0.5-1 MJ/kg
Melting and Extrusion	8-12 MJ/kg	20-25 MJ/kg	15-20 MJ/kg

The amount of energy consumption varies with the level of impurities, operating temperature needed, and the method opted to perform the process. For the current study, the energy consumptions are calculated using the standard methods and summarised in Table 3 and 4.

Total Energy Consumption for PLA Recycling (1 kg): [8]

$$\text{Total Energy} = (0.5 + 1 + 0.5 + 8) \text{ MJ} \approx 10 \text{ MJ/kg to } 14 \text{ MJ/kg} \quad (1)$$

Energy Consumption for 44.85 grams of PLA:

$$\text{Energy for } 44.85\text{g} = 44.85 \times \frac{10 \text{ MJ to } 14 \text{ MJ}}{1000\text{g}} \approx 0.45 \text{ MJ to } 0.63 \text{ MJ} \quad (2)$$

Total Energy Consumption for ABS Recycling (1 kg): For 1 kg of ABS, the total energy consumption for recycling is approximately:

$$\begin{aligned} \text{Total Energy} &= (0.5 + 1 + 0.5 + 20) \text{ MJ} \\ &= 22 \text{ MJ/kg to } 27 \text{ MJ/kg} \end{aligned} \quad (3)$$

Energy Consumption for 44.85 grams of ABS:

$$\text{Energy for } 44.85\text{g} = 44.85 \times \frac{22 \text{ MJ to } 27 \text{ MJ}}{1000\text{g}} \approx 0.98 \text{ MJ to } 1.21 \text{ MJ} \quad (4)$$

For 1 kg of PETG, the total energy required for recycling is approximately:

$$\begin{aligned} \text{Total Energy} &= 0.5 + 1 + 0.5 + 15 \\ &= 17 \text{ MJ/kg to } 24 \text{ MJ/kg} \end{aligned} \quad (5)$$

For 44.85 g of PETG:

$$\text{Energy for } 44.85 \text{ g} = 44.85 \text{ g} \times \frac{17-24 \text{ MJ}}{1000 \text{ g}} = 0.76 \text{ MJ to } 1.08 \text{ MJ} \quad (6)$$

Table 3: Total Energy Consumption in Recycling for Three Materials [8, 10,17]

Total Energy Consumption for 44.85g of Material used	
Materials	Range in MJ
PLA	0.45 MJ to 0.63 MJ
ABS	0.98 MJ to 1.21 MJ
PETG	0.76 MJ to 1.08 MJ

Table 4. Data for Material and Energy Consumption [19]

Materials	Material Consumption (g)		Manufacturing Phase Energy Consumption (kWh)	Recycling Phase Energy Consumption (kWh)
	Filter	Cube		
PLA	13.59	53.50	2.675	2.17
ABS	11.00	44.85	4.26	2.68
PETG	13.92	57.63	4.04	1.70

3.4 Impact Assessment

An impact assessment procedure can be employed to systematically analyze the environmental effects of a product [21]. The model illustrated in Figures 3.2, 3.3 and 3.4 allows for a comprehensive review of material and energy exchanges throughout the product's lifecycle. The CML method is recognized for breaking down the overall environmental impact of manufacturing processes and materials into specific, quantifiable categories. In this study, the environmental impacts of PLA, ABS and PETG are evaluated using the primary impact areas defined by the CML framework. The detailed impact category by the CMLO method are summarized in Table 6.

4 RESULTS AND DISCUSSION

The relative indicator outcomes for each project variant are presented in the normalized chart in Figure 2. Additionally, Figure 3 depicts the normalized chart for absolute values concerning the three main indicators: climate change, ecotoxicity: freshwater and human toxicity. The results for the other variants are represented in relation to the highest value, which has been normalized to 100% for each indicator.

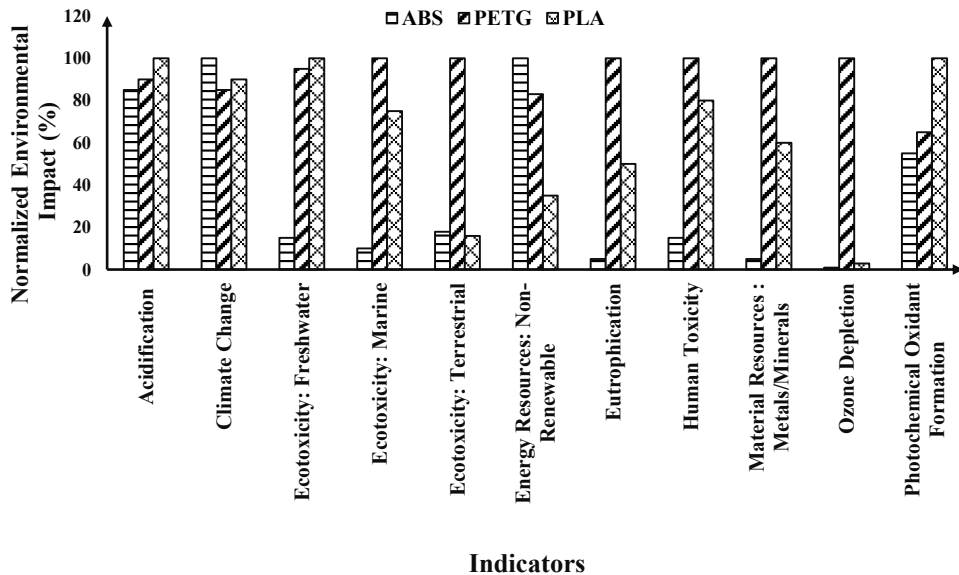


Figure 2. Normalized Environmental Impact Comparison

Figure 2 compares the normalized environmental impact across all CML categories, with the material having the greatest impact in each category set at 100%. ABS has the highest environmental burden in terms of climate change (4.45 kg CO₂-eq), acidification (0.0128 kg SO₂-eq), human toxicity (1.55 kg 1,4-DCB-eq) and formation of photochemical oxidants (0.000913 kg ethylene-eq) due to its energy-intensive processing and fossil fuel origin. In contrast, PLA shows better performance in terms of human toxicity (0.977 kg 1,4-DCB-eq) and global warming potential (3.96 kg CO₂-eq, which is 11% lower than that of ABS) because it is derived from renewable cellulose and is biodegradable. PETG typically falls in the middle range across most categories, outperforming ABS in climate

change metrics, yet it has higher marine ecotoxicity (6150 kg 1,4-DCB-eq compared to ABS's 630 kg 1,4-DCB-eq), likely due to the petrochemical by-products formed during its synthesis.

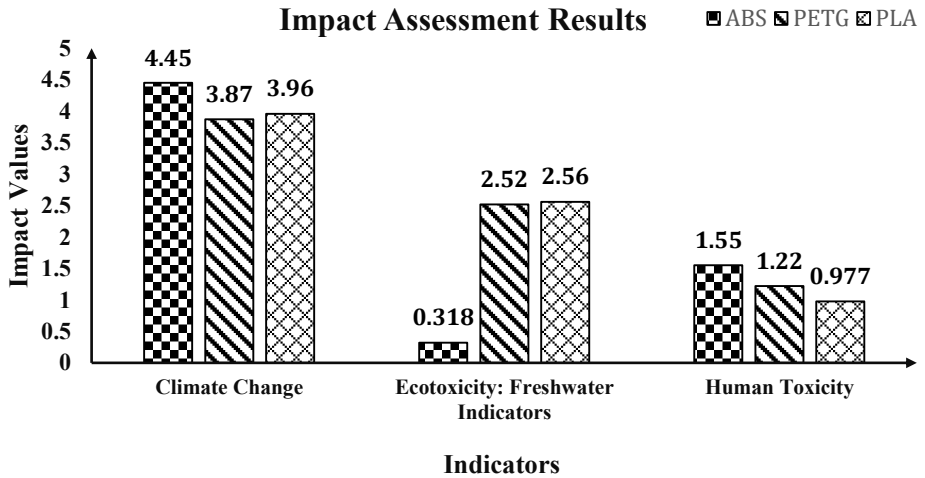


Figure 3 Impact Assessment Results (Absolute values)

The three principal indicators illustrated in Figure 3 are climate change, ecotoxicity: freshwater and human toxicity, each with its respective quantified impacts. The graph demonstrates that ABS (88.0 MJ) is significantly more prone to non-renewable energy depletion as it consumes 2.65 times more energy than PLA (33.2 MJ). Additionally, the impacts of PETG (6150 1,4-DCB-eq) and PLA (4600 1,4-DCB-eq) are notably higher than that of ABS (630 1,4-DCB-eq), by factors of 9.75 and 7.30, respectively, particularly regarding marine ecotoxicity. This indicates that the use of renewable materials may result in agricultural chemical residues, which should be taken into account during the procurement of feedstocks.

Figure 3.2 shows the integrated system model for PLA spanning four lifecycle stages. These stages include raw material extraction (origin of feedstock), manufacturing (energy usage during FDM printing at designated thermal parameters outlined in Table 1), the inert use phase and end-of-life recycling processes (discussed in Section 3.3.1). Each model pathway tracks material flows throughout these stages. The model framework demonstrates that energy inputs (shown as utility connections) vary according to the material being used. Manufacturing ABS requires 4.26 kWh, while PLA needs 2.675 kWh, both of which significantly impact the total environmental burdens. Similarly, model graphs can be created for ABS and PETG.

For a 125 cm³ functional unit, Table 5-6 depicts the environmental impacts across 10 CML categories. Key findings include: (i) Climate Change: ABS (4.45 kg CO₂-eq) exceed PLA (3.96 kg CO₂-eq) and PETG (3.87 kg CO₂-eq); (ii) Energy Resources (Non-Renewable): ABS (88.0 MJ) greatly outstrip PLA (33.2 MJ), highlighting its dependence on fossil fuels; (iii) Marine Eco-toxicity: PETG (6150 1,4-DCB-eq) and PLA (4600 1,4-DCB-eq) emerge as significant environmental concerns, reflecting sourcing issues. ABS (0.0128 kg SO₂-eq) show unexpectedly lower acidification potential than PLA (0.0149 kg SO₂-eq), likely due to

emissions from agricultural production associated with PLA, such as fertilizer application and machinery use.

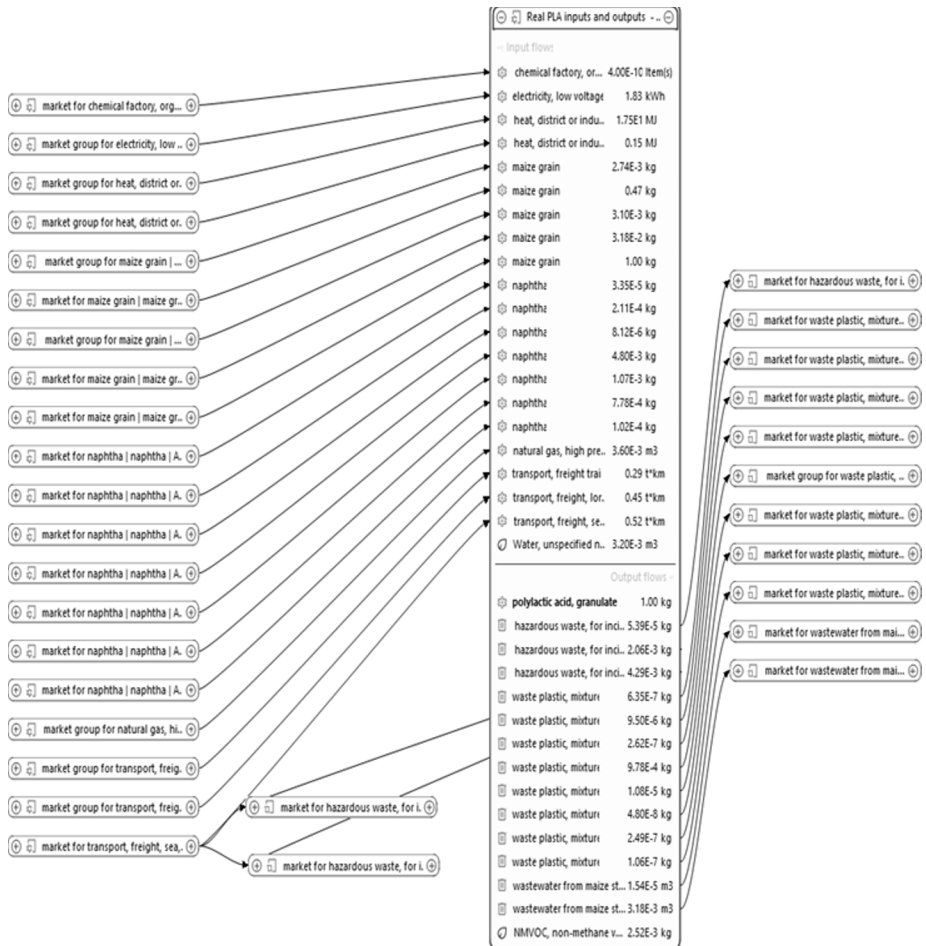


Figure 4. LCA model representation for PLA as filament materials

Table 5. Impact Assessment Results

Indicator	ABS	PETG	PLA	Unit (kg-Eq)
Acidification	0.0128	0.0132	0.0149	SO ₂
Climate Change	4.45	3.87	3.96	CO ₂
Ecotoxicity: Freshwater	0.318	2.52	2.56	1,4-DCB
Ecotoxicity: Marine	630	6150	4600	1,4-DCB
Ecotoxicity: Terrestrial	0.0148	0.0899	0.0113	1,4-DCB
Energy Resources: Non-Renewable	88.0	76.7	33.2	MJ

Eutrophication	0.00208	0.00274	0.00150	PO ₄
Human Toxicity	1.55	1.22	0.977	1,4-DCB
Material Resources: Metals/ Mineral	0.00000215	0.0000327	0.0000201	Sb
Ozone Depletion	0.0000000895	0.000000101	0.000000362	CFC
Photochemical Oxidant Formation	0.000913	0.00110	0.00176	Ethylene

Table 6. Comparison of Impact Category of PLA, ABS & PETG

Impact Category	PLA	ABS	PETG
Global Warming Potential (GWP)	Low (renewable resources, but still requires energy)	High (fossil fuel-based, energy-intensive)	Moderate (petrochemical-based, more efficient than ABS)
Acidification Potential	Low	High	Moderate to High
Eutrophication Potential	Moderate (due to agriculture)	High (due to NO ₂ emissions)	Moderate
Ozone Layer Depletion	Very Low	Moderate	Low
Photochemical Ozone Creation	Low	High	Moderate
Human Toxicity Potential	Low	High	Moderate

Tables 5 and 6 present the summary of the qualitative impact profiles for all materials and its comparison. PLA stands out as the preferred choice for environmentally aware manufacturing, as it demonstrates significant advantages in five out of six impact categories (GWP, acidification, ozone depletion, photochemical ozone formation and human toxicity). Nevertheless, PLA's nearly concerning marine ecotoxicity (4600 1,4-DCB-eq, compared to ABS's 630 1,4-DCB-eq) and its moderate eutrophication potential stemming from nitrogen runoff in agriculture raise additional environmental issues that require attention through effective waste management and adherence to agricultural best practices. In contrast, aside from its relatively low marine ecotoxicity (630 1,4-DCB-eq, the lowest among the three materials), ABS consistently underperforms in all categories, rendering it the least sustainable choice for mass production. While PETG incurs an environmental cost of 76.7 MJ of non-renewable energy, which is still 2.31 times greater than that of PLA, it serves as a suitable alternative for applications where the brittleness of PLA becomes a limitation.

5 CONCLUSIONS

The comparative analysis indicates that PLA is the eco-friendly option among the materials evaluated due to its renewable source, reduced emissions and ability to biodegrade. However, ABS indicate the highest environmental impact among all the assessed categories; it may be due to its petrochemical foundation and the incorporation of hazardous substances during its

production. In contrast, PETG outperforms ABS but falls short of PLA, particularly regarding eutrophication, acidification and potential for global warming. Moreover, the CML impact assessment provides a robust framework for measuring and comparing these environmental impacts.

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6 REFERENCES

- 1 The 17 Sustainable Development Goals. Available online: <https://sdgs.un.org/goals>. [Accessed: 12 December 2021].
- 2 Krishna LSR, Srikanth PJ. Evaluation of environmental impact of additive and subtractive manufacturing processes for sustainable manufacturing. *Materials Today: Proceedings* 2021; 45:3054–3060.
- 3 Koroneos CJ, Nanaki EA. Life cycle environmental impact assessment of a solar water heater. *Journal of Cleaner Production* 2012; 37:154–161.
- 4 Kolla M. Present and Future of 3D Printing. Available online: <https://www.fabheads.in/blogs/present-and-future-of-3d-printing/>. [Accessed: 12 December 2021]
- 5 Vashi Y, Anand R, Jayakrishna K, Rajyalakshmi G, Raj SA. Design and analysis of 3D printed UAV wheel. *Materials Today: Proceedings* 2021; 46: 8307–8312.
- 6 Shahrubudin N, Lee TC, Ramlan R. An overview on 3D printing technology: Technological, materials, and applications. *Procedia Manufacturing* 2019; 35: 1286–1296.
- 7 Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications, and challenges. *Composites Engineering* 2018; 143: Elsevier 172–196.
- 8 Zhu C, Li T, Mohideen MM, Hu P, Gupta R, Ramakrishna S, Liu Y. Realization of Circular Economy of 3D Printed Plastics: A Review. *Polymers*. 2021; 13(5):744.
- 9 Sangwan KS, Herrmann C, Egede P, Bhakar V, Singer J. Life Cycle Assessment of Arc Welding and Gas Welding Processes. *Procedia CIRP* 2016; 48:62–67.
- 10 Suárez L, Domínguez M. Sustainability, and environmental impact of fused deposition modelling (FDM) technologies. *International Journal of Advanced Manufacturing Technology* 2020; 106: 1267–1279, Feb. 2020.
- 11 Muñoz I, -Madrid JA, Muñoz MM. Life cycle assessment of integrated additive-subtractive concrete 3D printing. *The International Journal of Advanced Manufacturing Technology* 2021; 112: 2149–2159.
- 12 Ferreira VJ, Wolff D, Hornés A, Morata A, Torrell M, Tarancón A, Corchero C. 5 kW SOFC stack via 3D printing manufacturing: An evaluation of potential environmental benefits. *Applied Energy* 2021; 291.116803.
- 13 Kumar R, Rogall C, Thiede S, Sangwan KS, Herrmann C. Development of a Decision Support System for 3D Printing Processes based on Cyber Physical Production Systems. *Procedia CIRP* 2021; 98:348–353.
- 14 Ma H, Zhang Y, Jiao Z, Yang W, He X, Xie G, Li H. Comprehensive Assessment of the Environmental Impact of Fused Filament Fabrication Products Produced Under Various Performance Requirements. *Journal of The Institution of Engineers (India)* 2021; Series C: 102: 59–73.
- 15 Average CO2 emissions intensity of hourly electricity supply in India, 2018 and 2040 by scenario and average electricity demand in 2018, IEA, Paris. Available Online: <https://www.iea.org/data-and-statistics/charts/average-co2-emissions-intensity-of-hourly-electricity>. [Accessed: 18 November 2021]
- 16 Kumar R, Sharma H, Saran C, Tripathy TS, Sangwan KS, Herrmann C. A comparative study on the life cycle assessment of a 3D printed product with PLA, ABS & PETG materials. *Procedia CIRP*. 2022 Jan 1;107:15–20.
- 17 Wernet, G. Bauer C, Steubing B. The ecoinvent database version 3 (part I): overview and methodology; *The International Journal of Life Cycle Assessment* 2015; 21:1218–1230.
- 18 Bajpai R, Choudhary K, Srivastava A, Sangwan KS, Singh M. Environmental impact assessment of fly ash and silica fume based geopolymer concrete. *Journal of Cleaner Production* 2020; 254: 120147.