



Environmental sustainability and economic assessment of additive manufacturing: the influence of polymer type and layer definition

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Abstract

Additive manufacturing (AM) has gained widespread attention due to its potential to reduce material waste, lower energy consumption, and a wide variety of applications. However, its environmental and economic sustainability is widely debated. This study carried out a Life cycle assessment (LCA) and an economic analysis (EA) to evaluate the environmental sustainability and economic aspects of five different thermoplastic filaments at three distinct layer definitions. The environmental assessment of materials with identical geometric conditions indicated that impacts increased significantly with printing resolution, primarily due to longer printing times and higher electricity consumption. Global warming (GW) ranged from 4.80E-02 kg CO₂ eq for polylactic acid (PLA) in draft mode (DM) to 1.51E-01 kg CO₂ eq for acrylonitrile butadiene-styrene (ABS) in ultradetail mode (UM). Across materials, polyethylene terephthalate glycol (PETG) and PLA generally exhibited lower environmental impacts, while high-quality polyvinyl chloride (FLEX) showed higher impacts, within the conditions analysed in this study. The EA reported that FLEX was the most expensive material, ranging from 2.02 to 2.99 EUR per printed item and from 0.60 to 0.15 EUR per layer, while PLA showed the lowest costs ranging from 0.70 to 2.57 EUR and 0.21 to 0.13 EUR per layer. The results should be interpreted as a comparison of filament-printing combinations under fixed geometric and process conditions, rather than as a general ranking of material sustainability. This study contributes to the scientific literature by proposing a new perspective on the sustainability assessment of AM materials through the synergy between LCA and EA.

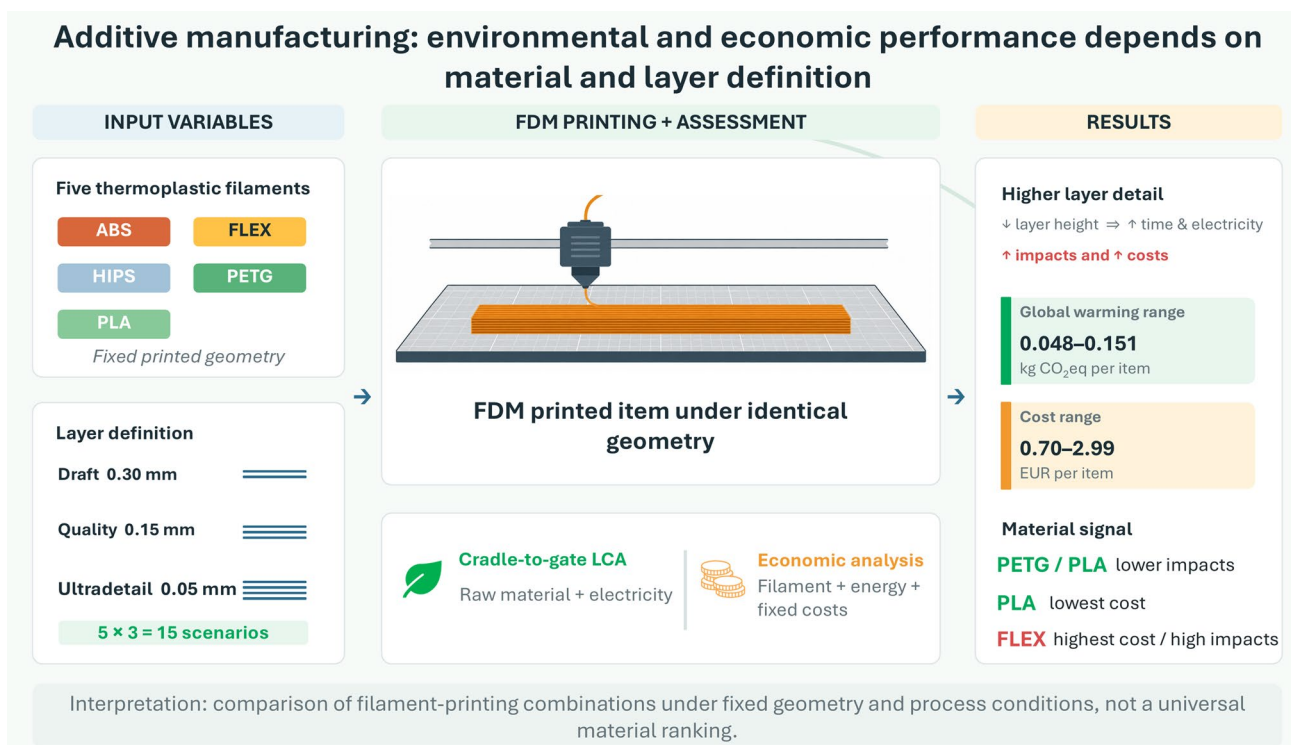
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Graphical Abstract



Keywords Life cycle assessment · 3D printing · Additive manufacturing · Climate change · Environmental impacts · Economic analysis

Abbreviations

ABS	Acrylonitrile-butadiene—styrene
AM	Additive manufacturing
DM	Draft mode
EA	Economic analysis
FDM	Fused deposition modelling
FLEX	High-quality polyvinyl chloride
FRS	Fossil resource scarcity
GW	Global warming
HIPS	High impact polystyrene
LCA	Life cycle assessment
PETG	Polyethylene terephthalate glycol
PLA	Polylactic acid
PM	Fine particulate matter formation
QM	Quality mode
UM	Ultradetail mode
WC	Water consumption

Introduction

Growing concerns about environmental sustainability have led to increase attention to production processes and their impact on the world (Ahmad et al. 2022; Zahoor et al. 2022). The green transition to more sustainable production methods is essential to mitigate climate change, reduce resource depletion, and minimise waste production (Baltrocchi et al. 2024). In this context, additive manufacturing (AM), commonly known as 3D printing, has emerged as a promising alternative to traditional manufacturing due to its potential to reduce material waste and enable localised production (Al Rashid and Koç 2023). However, despite these advantages, AM is not inherently sustainable, mainly due to energy consumption (Ford and Despeisse 2016). Its environmental impact varies significantly depending on the materials used, the energy requirements of different printing processes, and the post-processing steps required for functionalisation (Alfaify et al. 2020; Cobos et al. 2025). The selection of printing materials plays a pivotal role in the environmental impacts of 3D-printed objects (García et al. 2020; Ibáñez-García et al. 2021; Kartal and Kaptan 2024). In addition, recent studies have highlighted how

polymer-based materials can contribute to emerging environmental concerns beyond traditional impact categories. For instance, the release of microplastics and microfibers from synthetic materials has been increasingly recognised as a critical issue, with implications for environmental pollution and ecosystem health (Luzi et al. 2025).

AM encompasses several primary technologies, each defined by the form of raw material and the method of layer construction. Material extrusion, most commonly Fused Deposition Modelling (FDM), employs thermoplastic filaments extruded through a heated nozzle to build parts layer-by-layer (Gibson et al. 2015; Mukoroh et al. 2024). Vat photopolymerisation, including stereolithography, digital light processing, and masked stereolithography, utilises a light source to selectively cure liquid photopolymer resin with high precision (Ngo et al. 2018). Powder bed fusion methods, such as selective laser sintering and selective laser melting, use a laser to sinter or melt powder materials, polymers or metals, into solid geometries (DebRoy et al. 2018; Castanon-Jano et al. 2024). Other notable processes include material jetting, which deposits photopolymers in droplet form and cures them with UV light, and binder jetting, wherein a liquid binder is used to selectively join powder particles, typically followed by post-processing steps like sintering or infiltration (Guo and Leu 2013). In this study, an FDM 3D printer is used. In particular, FDM printing technique is affordable, easy to use, and ideal for functional prototypes, but they offer lower resolution and surface finish compared to resin or powder-based printers. In contrast, resin and powder methods provide higher detail and material strength but come with higher costs, more complex handling, and post-processing requirements (Ligon et al. 2017; Jandyal et al. 2022; Alarifi 2024).

Thermoplastic polymers are the most used materials in FDM (Cascales et al. 2024). Among these materials, acrylonitrile butadiene–styrene (ABS), high-quality polyvinyl chloride (FLEX), high impact polystyrene (HIPS), polyethylene terephthalate glycol (PETG), and polylactic acid (PLA) have distinct environmental impacts based on their origin, recyclability, and biodegradability (Wojtyła et al. 2017). While PLA, for example, is derived from renewable resources, ABS and HIPS are petroleum-based and generally have higher impacts (Sowmya et al. 2018). In addition to the type of material, the print resolution, defined by layer height, affects energy consumption and material efficiency (Del Rosario et al. 2022; Perrot et al. 2024). High-resolution prints require more energy and longer processing times, while low-resolution settings could lead to higher material waste (Ruiz-Morales et al. 2017). It is necessary to evaluate different combinations of materials and processes to determine the most sustainable solution in economic and environmental terms (Pavon et al. 2020).

Life Cycle Assessment (LCA) methodology can be useful to evaluate the environmental sustainability of a product, service, or production process. LCA is a standardised methodology that follows the ISO 14040/14044 (ISO 2006a, b) and it allows to estimate the environmental impacts from raw materials extraction to the end-of-life through production process, distribution, use, and final disposal. It proved to be an essential tool for assessing sustainability and facilitating informed decision-making, as it identifies environmental impacts and areas for potential improvement through comparative analyses (Baltrocchi et al. 2025).

However, environmental sustainability is not sufficient to provide a comprehensive evaluation of the sustainability of a process. The results about environmental pressures provided by LCA should be integrated with economic considerations evaluating the feasibility in short and long term of the adoption of the proposed solutions. Unlike traditional cost assessments that focus only on the initial investment, economic analysis accounts for costs related to raw materials, energy consumption, maintenance, operational efficiency, and end-of-life disposal (Bot et al. 2022). Integrating economic analysis with LCA provides a more robust framework for decision-making, ensuring that sustainability strategies are not only environmentally viable but also economically feasible (Larsen et al. 2022).

In recent years, several studies have applied LCA analysis to quantify the environmental impact of 3D printing technology. For instance, Alex et al. (2025) conducted a comparative LCA of PLA-based material extrusion 3D printing versus injection moulding, highlighting that optimised print parameters can significantly reduce environmental impacts. Andreozzi et al. (2024) performed an LCA comparing high-performance fibre-reinforced composite printing with traditional moulding technology, emphasising the potential benefits of 3D printing in reducing material waste and energy consumption. Again, Espada et al. (2023) evaluated the environmental impact of 3D printing using novel polymeric materials, identifying solvent usage as precursor synthesis as a major impact contributor. However, these studies provide essential benchmarks, and they primarily focus on single-material assessments or isolated manufacturing techniques, lacking a comprehensive comparison between different filaments and print settings.

Regarding the economic analysis (EA), previous studies have reported that process parameters and material choice significantly influence production cost of AM. For instance, bio-based materials such as PLA may have lower environmental impacts due to their renewable origin. However, they can sometimes result in higher production costs due to lower mechanical performance and higher replacement rates (Agrawal 2021). Furthermore, high-resolution printing increases energy consumption, affecting economic performance (Herrmann et al. 2011). Al Masri et al.

(2025) highlighted how economic evaluations in 3D printing are still affected by methodological inconsistencies, limited cost data availability, and a lack of tools tailored to AM processes. Similarly, Mecheter et al. (2023) reported that EA remain underrepresented compared to environmental assessments and studies that integrated LCA-LCC approaches are still rare. As a result, most studies focus primarily on environmental impact, often neglecting the economic aspects, and only a few contributions provide a combined assessment of different process parameters. This research tries to fill this gap evaluating environmental and economic performance on different filaments and printing resolutions, allowing for a more comprehensive comparison within a consistent methodological framework.

This study performed a systematic LCA and an EA of a 3D-printed item with identical geometric conditions made in (i) five different thermoplastic filaments (ABS, FLEX, HIPS, PETG, PLA) and (ii) three distinct print resolutions (0.05 mm, 0.15 mm, 0.30 mm). In detail, the research aims to identify the most environmentally sustainable and most cost-benefits filament-print setting combination. It should be specified that the analysis is aimed at comparing materials produced with different polymers but with the same geometry, without considering their mechanical properties and potential end-use suitability. Therefore, the work does not provide indications on general material sustainability performance but only on the modelled manufacturing conditions. Compared to previous studies, this research introduces a broader comparative framework, evaluating different filaments in combination with various processes and providing more robust recommendations for sustainable and cost-effective production. These results will be useful both for the scientific community and technical stakeholders involved in the production and management of AM.

Materials and methods

Goal and scope definition

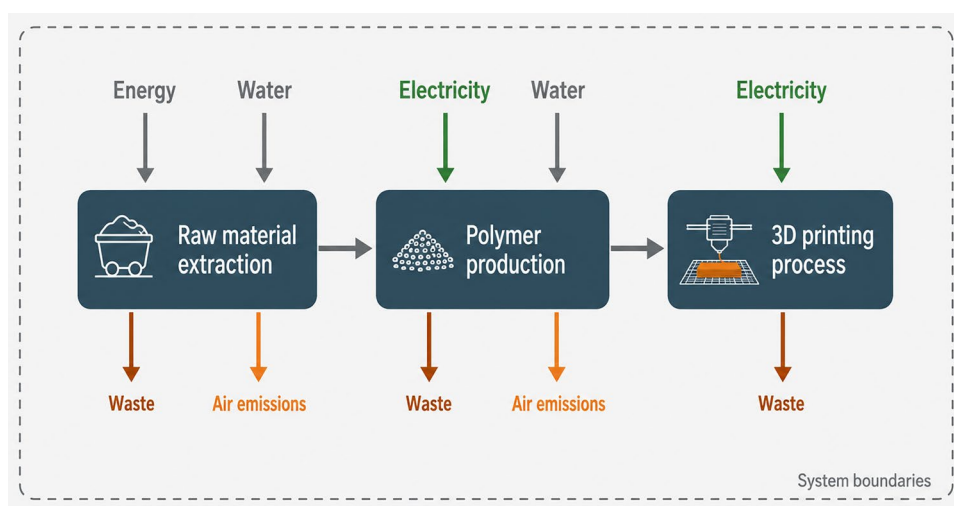
The research aimed to evaluate the environmental performance of a 3D-printed item considering the different combinations of five different filaments and three print settings with the aim of identifying the best environmental and cost combination. In total, 15 scenarios were evaluated. The study addresses two main research questions:

What is the most environmentally sustainable filament material for each print setting?

How do costs change when increasing print resolution?

LCA and an EA were carried out. The LCA was carried out using SimaPro v10.2 software (Goedkoop et al. 2016) and Ecoinvent v3.11 database (Wernet et al. 2016). The environmental profile was evaluated using ReCiPe 2016 v1.07 impact assessment method (Goedkoop et al. 2009). The system boundaries follow a cradle-to-gate approach and include raw material production and the printing process, represented by filament consumption and electricity usage (Fig. 1). The time and geographic boundaries are 2024 and Spain, respectively. The functional unit is defined as one 3D-printed item with fixed geometry. This choice enables a consistent comparison of environmental and economic impacts across different materials and printing resolutions. All inventory data, including filament mass, printing time, and energy consumption, were obtained from real printing simulations using Prusa Slicer v2.9.0 software (Chen et al. 2021) with printer Original Prusa i3 MK3®. Therefore, the analysed scenarios are representative of realistic operating conditions and not based on arbitrary assumptions. It is acknowledged that different materials exhibit different

Fig. 1 System boundaries of the study based on cradle-to-gate approach



mechanical and functional properties. However, the objective of this study is to compare the environmental and economic performance of materials and process parameters under identical geometric conditions, rather than to assess functionally equivalent end-use products. This limitation is considered in the interpretation of results.

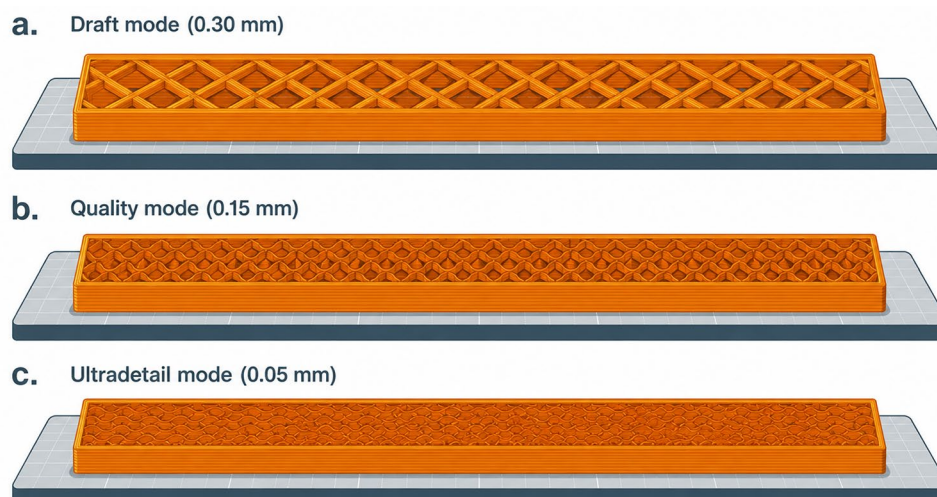
Printing activities

The 3D-printed item considered in the analysis is a solid with a length of 165 mm of length, 20 mm of width, and 6 mm of height (Figure S1). The printing simulations were carried out through Prusa Slicer v2.9.0 software (Chen et al. 2021) with printer Original Prusa i3 MK3@. This machine has been used in several studies such as (Hu 2021) and (Tulică et al. 2023). The printing simulations have been made considering five different materials: (i) ABS, (ii) FLEX, (iii) HIPS, (iv) and (v) PLA. ABS is a strong, impact-resistant, and heat-resistant material, but it tends to warp and requires a heated bed, making it suitable for durable parts. FLEX is elastic and ideal for flexible components, but it is more challenging to print due to adhesion and extrusion difficulties. HIPS is similar to ABS but lighter, making it excellent support material for dual-extrusion printing.

Table 1 Feature of filament materials, average printing nozzle, and bed temperature (T = temperature)

Filament	Diameter (mm)	Density (g cm ⁻³)	T nozzle (°C)	T bed (°C)
ABS	1.75	1.04	255	100
FLEX	1.75	1.22	240	50
HIPS	1.75	1.04	230	100
PETG	1.75	1.27	230	85
PLA	1.75	1.24	215	60

Fig. 2 Internal texture of the three layers print settings: **a** DM-0.30 mm, **b** QM-0.15 mm and **c** UM-0.05 mm



PETG offers a balance between PLA and ABS, combining strength, impact resistance, and slight flexibility with good layer adhesion and chemical resistance. PLA, the easiest to print, is biodegradable and ideal for prototypes, though it is more brittle and less heat-resistant compared to ABS or PETG (Gregor-Svetec 2022; Diniță et al. 2023; Prajapati et al. 2024). The features of materials and the average operating printing temperature of the nozzle and bed are reported in Table 1.

For each scenario, the analysis took into consideration three sub-scenarios with different layer thicknesses: draft mode (DM): 0.30 mm; quality mode (QM): 0.15 mm; and ultradetail mode (UM): 0.05 mm. Each of these settings significantly influences the internal texture of the 3D-printed item; the lower the thickness of each layer the higher the detail of the item. The DM results in a coarser internal structure with visible layer lines and a rougher surface finish, making it suitable for rapid printing where fine details are less critical (Fig. 2a). The filling pattern and filling density applied are the same in all samples. The QM offers a balanced compromise between speed and precision, producing a smoother texture with finer layer adhesion (Fig. 2b). Finally, the UM achieves the highest level of detail, minimising visible layer lines and creating a dense, refined internal texture that enhances both the mechanical properties and aesthetic quality of the printed figure (Fig. 2c).

Life cycle inventory for LCA

The primary data have been collected in the 3D printing lab of the Instituto Universitario de Investigación de Tecnología de los Materiales of the Universitat Politècnica de València and referred to 2024. Filament materials production processes have been sourced from all materials associated with the products using the Ecoinvent v3.11 database. As for printing process, it was using a process

that simulated 3D printing and electricity consumption from Spain country mix. Spools and filament packaging have been excluded from the inventory as they have been reused many times and materials derived from ordinary and extraordinary maintenance of the printer. The electricity consumption (EC) has been calculated according to Eq. 1:

$$EC_{ij}(Wh) = P_{ij} * T_{ij} \quad (1)$$

where P_{ij} is the printer power in Watt and T_{ij} is the printing time in hours of the printing process of the i -th materials in the j -th printing settings. The printer powers and printing times for each material and settings are reported in Table S1. Filament mass, printing time, and power consumption were obtained directly from the Prusa Slicer v2.9.0 software (Chen et al. 2021) with printer Original Prusa i3 MK3®. In FDM processes, material consumption is determined by the software-generated toolpath, which depends on factors such as layer height, extrusion strategy, perimeter definition, and path optimisation. Consequently, even for identical geometries, variations in filament usage may occur depending on the print resolution and material. Therefore, the reported values reflect realistic printing conditions and should be interpreted as process-based outputs rather than purely geometric estimates. In Table 2, all data that are considered for each print settings scenario and their Ecoinvent database process are reported.

Evaluation of costs

The details of inventory data input are reported in Table S2. Microsoft Excel tool was used to calculate the values using the following equations. First, variable costs were evaluated for each scenario and subscenario considering two different aspects: material and energy costs. The filament cost (FC) has been calculated according to Eq. 2:

$$FC_i(EUR) = FCK_i / FW_{ij} \quad (2)$$

where FCK_i is the filament cost per kg, while FW_{ij} is the filament weight used of the i -th materials in the j -th printing settings. The energy cost (ECS) is calculated according to Eq. 3:

$$ECS_{ij} = P_i / ET \quad (3)$$

where P_i is the printer power and ET is the electricity tariff of the i -th materials in the j -th printing settings.

The fixed costs, expenses that remain constant regardless of production volume, are reported below, including printer depreciation, repair expenses, and other estimated charge.

The printer depreciation (PD) is calculated according to Eq. 4:

$$PD(EUR) = PP / (PL * DU) \quad (4)$$

where PP is the printer purchase cost, PL is the printer lifetime, and DU is the daily usage. The cost associated with the printer repairs (PR) is expressed in Eq. 5:

$$PR(EUR) = [(PP * RCS) / PL] * T_{ij} \quad (5)$$

where RCS is the percentage repair cost, while T_{ij} is the printing time in hours of the printing process of the i -th materials in the j -th printing settings.

There are some costs (FR_{ij}) associated with the failures of the i -th materials in the j -th printing settings that are estimated as 10% of the total and other generic cost (OC) estimated at 0.10 EUR per printed item.

The total costs (TC) of the printing process of the i -th materials in the j -th printing settings is the sum of all previous costs and it is calculated according to Eq. 6:

$$TC_{ij}(EUR \text{ item}^{-1}) = FC_i + ECS_{ij} + PD + PR + FR_{ij} + OC \quad (6)$$

Furthermore, to understand how the texture affects the total cost, the cost per layer (TCL) of the i -th materials in the j -th printing settings was evaluated according to Eq. 7:

$$TCL_{ij}(EUR \text{ mm item}^{-1}) = TC_{ij} * LT_j \quad (7)$$

where LT_j is the layer thickness in millimetres of j -th printing settings.

Capital costs are implicitly accounted for through depreciation, which spreads the printer's purchase cost over its lifespan and use. Therefore, capital costs are not included as a separate item in the total cost calculation to avoid double counting. Maintenance and repair costs, however, are considered additional operating expenses.

Results

Environmental sustainability

The results are reported for four key environmental impact indicators: (i) Global warming (GW), (ii) Fine particulate matter formation (PM), (iii) Fossil resource scarcity (FRS), and (iv) Water consumption (WC). These indicators capture the main environmental pressures associated with AM processes, including energy-related emissions, air pollution, depletion of fossil resources, and water use. Together, they provide a comprehensive representation of the most relevant environmental impacts linked to material production and electricity consumption, which are the dominant contributors in FDM processes. Focusing on these indicators allows for a robust and interpretable assessment of environmental performance, while maintaining clarity and comparability

Table 2 Life Cycle Inventory analysis (LCI) data and database input. The quantities are referred to 3D-printed item that was considered as functional unit and to print settings (GLO: global; ES: Spain)

Process	Quantity	Unit	Ecoinvent database
ABS			
ABS process production	DM: 10.27 QM: 10.00 UM: 9.89	g	Acrylonitrile–butadiene–styrene copolymer {GLO} market for acrylonitrile–butadiene–styrene copolymer Cut-off, U
Printing process	DM: 68.40 QM: 126.00 UM: 494.00	Wh	Electricity, low voltage {ES} market for electricity, low voltage Cut-off, U
FLEX			
FLEX process production	DM: 13.85 QM: 13.48 UM: 13.34	g	Polyvinylchloride, bulk polymerised {GLO} market for polyvinylchloride, bulk polymerised Cut-off, U
Printing process	DM: 230.00 QM: 225.00 UM: 417.00	Wh	Electricity, low voltage {ES} market for electricity, low voltage Cut-off, U
HIPS			
HIPS process production	DM: 10.27 QM: 10.00 UM: 9.89	g	Polystyrene, high impact {GLO} market for polystyrene, high impact Cut-off, U
Printing process	DM: 57.00 QM: 105.00 UM: 412.00	Wh	Electricity, low voltage {ES} market for electricity, low voltage Cut-off, U
PETG			
PETG process production	DM: 10.84 QM: 12.21 UM: 12.08	g	Polyethylene terephthalate, granulate, amorphous {RER} polyethylene terephthalate production, granulate, amorphous Cut-off, U
Printing process	DM: 60.00 QM: 105.00 UM: 412.00	Wh	Electricity, low voltage {ES} market for electricity, low voltage Cut-off, U
PLA			
PLA process production	DM: 12.25 QM: 11.92 UM: 11.80	g	Polylactic acid, granulate {GLO} market for polylactic acid, granulate Cut-off, U
Printing process	DM: 45.60 QM: 84.00 UM: 330.00	Wh	Electricity, low voltage {ES} market for electricity, low voltage Cut-off, U

across different filaments and printing resolutions. Additional indicators are reported in Table S3.

A consistent trend is observed for all indicators, with a significant increase in environmental impact as the print resolution increases, moving from draft mode (DM) to ultradetail mode (UM). Regarding GW (Fig. 3a), the impact increased by around 100% to 200% depending on the material: ABS increased from 6.40E-02 kg CO₂ eq (DM) to 1.51E-01 kg CO₂ eq (UM), and PETG from 5.03E-02 to 1.28E-01 kg CO₂ eq. This increase was directly linked to the significant increase in print times and electricity consumption at higher resolutions. Considering all materials, PETG

and PLA generally had a lower environmental impact than ABS, FLEX, and HIPS for most indicators, although the differences depend on the impact category considered. FLEX consistently showed among the highest impacts in DM, particularly for GW and PM, reaching values above 8.53E-02 kg CO₂ eq and 1.07E-04 kg PM_{2.5} eq, respectively, mainly due to increased material demand. As reported in Fig. 3b, PM results followed a similar trend, with increases ranging from around 80% to 180% from DM to UM, confirming the dominant role of electricity-related emissions. For instance, ABS increased from 5.68E-05 to 1.69E-04 kg PM_{2.5} eq, while PETG and PLA showed comparable relative growth.

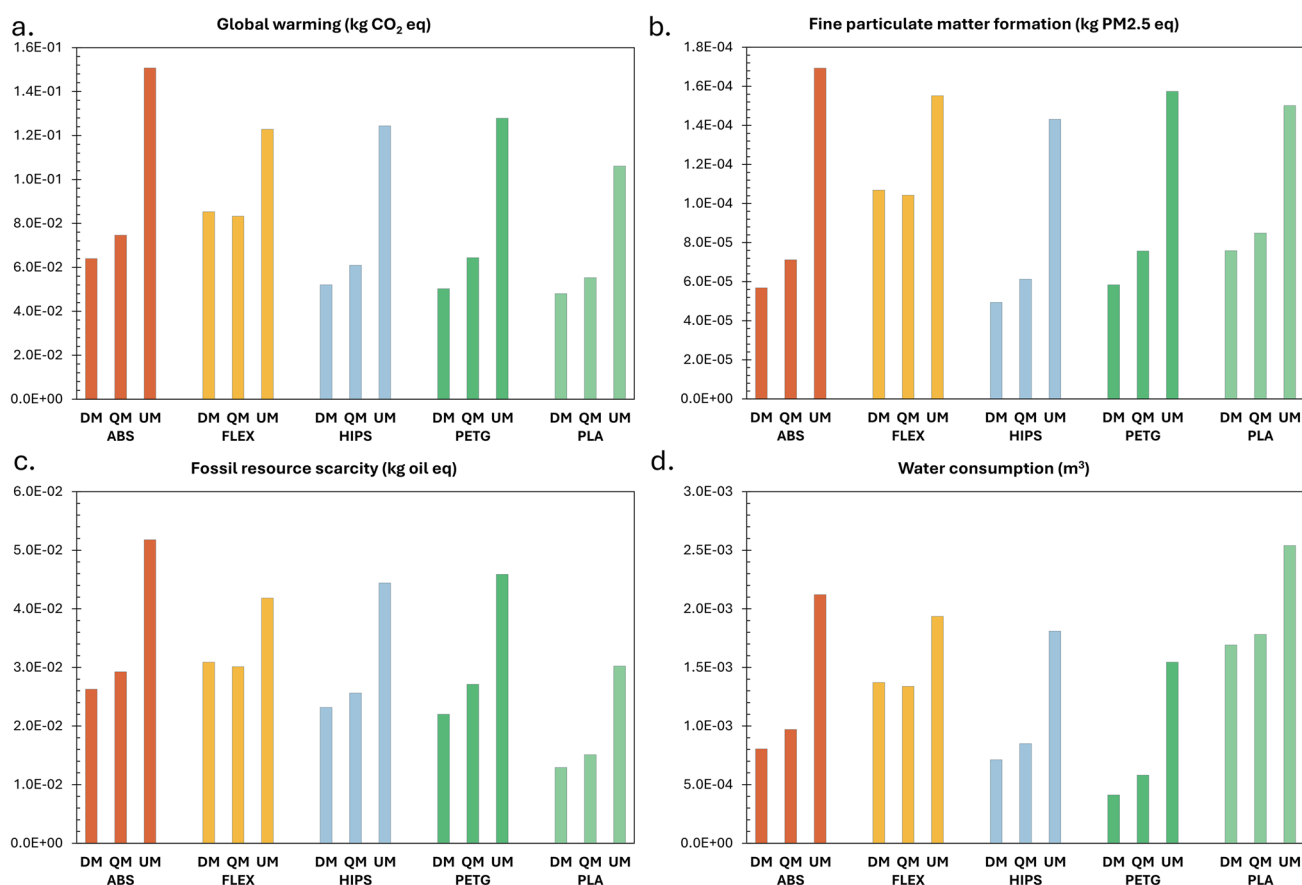


Fig. 3 Environmental impacts results per one 3D-printed item

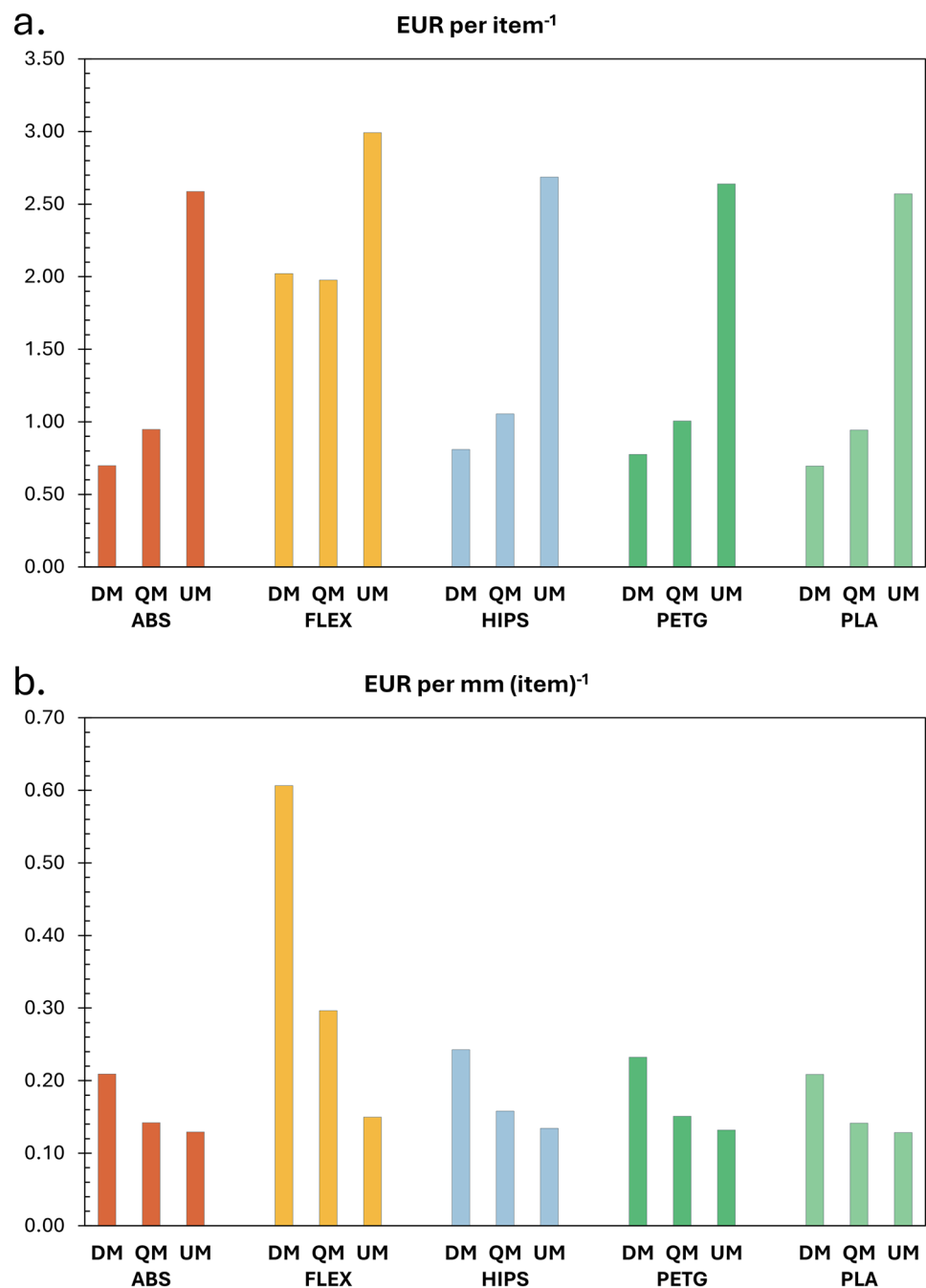
FRS indicator (Fig. 3c) showed a clear dependence on both material type and resolution, with increases ranging from around 70% to 150%. ABS and PETG reached values close to 5.00E-02 kg oil eq for UM printing resolution, while PLA remained relatively lower. Finally, WC (Fig. 3d) also increased with resolution, although with greater variability between materials. Specifically, ABS showed an increase from 8.0E-04 to 2.12E-03 m³ while PLA reached values up to 2.54E-03 m³ in UM. The relative increase varied between around 80% and 170%, reflecting differences in process production. Overall, while material choice influences environmental performance, print resolution emerges as a key driver of impacts, particularly for energy-related categories. In some cases, the increased electricity consumption associated with higher resolution can outweigh the differences between materials, highlighting the importance of process optimisation to reduce the environmental impact of FDM printing. Among the analysed materials, PETG and PLA generally showed the lowest environmental impacts across most indicators and printing settings, whereas FLEX consistently exhibited the highest impacts, particularly due to its higher material demand and the impacts of their process production. The environmental impact associated with

materials production is strongly influenced by the energy intensity of polymer manufacturing processes. Differences in energy requirements among filaments contribute significantly to the observed variation in environmental performance, particularly for impact categories related to energy consumption, highlighting the importance of considering production-related energy requirements when comparing materials.

Economic aspects

The results of the EA per item are reported in Fig. 4a. In the DM setting, the most expensive production process is the printing of FLEX with a total of 2.02 EUR. This is due to the quantity of polymer used during the process. Furthermore, this polymer had a higher purchase cost than others, which had similar costs to each other. HIPS printing cost was 0.81 EUR, followed by PETG with 0.81 EUR, while ABS and PLA with 0.70 EUR. Moving to the QM setting, FLEX printing was still the most expensive process (1.98 EUR), around double that of the others: 1.05 EUR for HIPS, 1.01 EUR for PETG, 0.95 EUR for ABS and 0.94 EUR for PLA. Finally, the difference between FLEX and other materials

Fig. 4 Economic analysis results (a) per EUR per item⁻¹ and (b) per EUR per mm (item)⁻¹



was significantly smaller in the UM setting. In fact, FLEX printing had a total cost of 2.99 EUR, followed by HIPS with 2.69 EUR, PETG with 2.64 EUR, ABS with 2.59 EUR and PLA with 2.57 EUR. In general, in the DM and QM settings, FLEX was significantly more expensive than the others, while the difference decreased in the UM setting. Among others, HIPS printing was generally the most expensive process, while PLA printing was the cheapest. The cost of the printing process was mainly influenced by the purchase cost of the polymer and the quantity used. Other parameters, such as the electrical energy used, affect the final cost less.

However, FLEX in the DM setting had the impacts higher than in QM setting. This is due to the material type, which requires a slightly higher printing time in the DM setting (2.30 h) than in the QM setting (2.25 h).

The results regarding the cost per layer are shown in Fig. 4b. This indicator is not a direct economic performance measure, but a comparative metric to understand the relationship between layer resolution and cost distribution. The DM setting presented the higher cost per layer, followed by the QM and UM settings. However, the cost difference between materials across different settings

remained unchanged. FLEX had the higher cost in each setting (0.61, 0.30, 0.15 EUR per mm in DM, QM, and UM settings, respectively), followed by HIPS (0.24, 0.16, 0.13 EUR per mm in DM, QM, and UM settings, respectively), PETG (0.23, 0.15, 0.13 EUR per mm in DM, QM and UM settings, respectively), ABS (0.21, 0.14, 0.13 EUR per mm in DM, QM, and UM settings, respectively) and PLA (0.21, 0.14, 0.13 EUR settings, per mm in DM, QM, and UM, respectively). Interestingly, the difference in cost per mm between DM and QM was very low; on average was around 10%, only in FLEX was it double. Furthermore, for a single item, the production cost between the DM detail and the UM on average tripled, while for cost per mm the increase was on average around 30%.

Discussion

Consideration about the results

This study comprehensively evaluates the environmental sustainability and economic aspects of five different 3D printing materials and three settings. The LCA results indicated a consistent trend across all materials, with impacts significantly increasing from DM to UM. GW increased by up to around 200% depending on the material, primarily driven by the substantial rise in printing time and associated electricity consumption. These results highlight that print resolution is a key factor in environmental performance, in some cases more important than material differences. While material manufacturing remains a significant factor, the role of electricity becomes increasingly important at higher resolutions, especially for materials with a less impactful manufacturing process. This confirms that process parameters, and especially energy requirements, play a crucial role in the environmental impact of FDM printing.

The analysis aimed to compare materials produced with different polymers but with the same geometry. Therefore, the results do not provide indications on general material sustainability performance but only on the modelled manufacturing conditions. About the different materials, PETG and PLA appeared to exhibit the lowest environmental impact compared to ABS, FLEX, and HIPS, although differences depend on the specific indicator and printing conditions. In contrast, FLEX consistently seemed to exhibit higher impacts, mainly due to greater material requirements. However, these results should be interpreted within the specific system boundaries and assumptions of the study, as variations in electricity mix, material datasets, and process conditions may influence the relative performance of materials.

The EA indicated that filament cost represents the dominant contribution across all settings, with FLEX appearing

to be the most expensive material due to its higher purchase price and required quantity (ranging from 2.02 to 2.99 EUR). In contrast, PLA seemed the most cost-effective filament across all print settings, ranging from 0.70 to 2.57 EUR, making it a favourable option for budget-conscious applications. The differences in energy consumption between print settings further influenced costs, with UM settings leading to a notable increase in overall expenses due to prolonged electricity usage. However, considering the costs per mm, the findings are the opposite; DM was the most expensive setting per layer. However, the cost per item difference between the different settings was high, around 300% increase between the DM and the UM, while for cost per mm, the increase was around 30% between the UM and the DM settings.

A key finding of this analysis is that cost and environmental impact do not always coincide. Predictably, increasing the print quality will increase the costs, but it is also clear that some materials are more advantageous than others. For example, FLEX increased the cost of around 48% between DM and UM settings, while ABS had an increase of around 270%. Furthermore, analysing the EUR per mm, some materials respond better than others in terms of the quality-cost ratio. For instance, FLEX seemed to be one of the worst with an increase of 75%, while ABS and PLA were the best solutions with around 38%. This duality is crucial for 3D printing decision-makers who are navigating material choices. For example, while PETG demonstrated the lowest environmental impact, it is not as cost-effective as PLA, which guarantees a better balance between costs and environmental sustainability. Therefore, the ranking of materials should be considered indicative and may change under alternative electricity mixes or industrial-scale printing conditions.

Policy implications

These findings have several implications for improving the sustainability of AM. First, integrating recycled materials into filament materials production can significantly reduce environmental impacts from raw material extraction. Several studies have shown that recycled thermoplastic filaments can increase the sustainability of the printing process (Sola and Trinchi 2023; Ibrahim et al. 2024). Second, optimising print settings can be crucial in minimising costs and emissions. While high-resolution prints provide superior detail, they significantly increased energy consumption. Manufacturers and users should consider whether such fine resolutions are necessary for their applications or whether lower-resolution settings could suffice without compromising functionality. The findings support the need for regulatory frameworks and industry standards that encourage the adoption of eco-friendly filaments and energy-efficient printing technologies. Additionally, incentives for using sustainable materials, such

as tax breaks, Environmental Product Declarations (EPDs), and certification schemes, could accelerate the transition to sustainable AM practices.

Limitations and future development

The main limitation of this study is that it addresses environmental sustainability and economic aspects based on an item made from different polymers, without considering the intended use. However, it is important to note that these materials have distinct properties that influence their usability and performance in different applications. For example, PLA is known for its biodegradability and ease of printing, making it suitable for consumer applications, but it has lower heat resistance (Taib et al. 2023). In contrast, PETG offers better mechanical strength and higher impact resistance, making it more suitable for functional parts that require durability (Valvez et al. 2022; Lakshman Sri et al. 2024). This variation in material properties raises a crucial consideration: the intended use of the printed item can significantly justify the costs associated with each material. Higher initial costs for PETG, while potentially less sustainable, may be justified in applications where performance, strength, and longevity are essential. In these cases, the trade-off between environmental impact and material functionality adds complexity to the decision-making process, highlighting the need for a comprehensive evaluation framework that integrates material performance criteria with economic and environmental considerations. In summary, the interaction between cost, environmental impact, and material properties is critical, and decision-makers should consider the specific requirements of their applications when selecting materials for AM.

Another limitation concerns the use of primary data coming from a specific laboratory. While this approach allows for a controlled comparison of process parameters, differences in mechanical performance between materials may affect their suitability for specific applications. In fact, variations in printing technologies, shapes, energy mixes, and filament materials may influence the results (Harris et al. 2019; Kristiawan et al. 2021; Mecheter and Tarlochan 2023). In the future, the analysis can be expanded by including a wider range of printing technologies, evaluating different geographical contexts and using different materials. Moreover, this study does not provide a sensitivity analysis, meaning that our findings should be interpreted strictly within the specific boundary conditions and operational parameters defined in this work. Although the results are based on empirical data, variations in production scale, processing intensity, printing duration, and energy mix could influence the results. Consequently, the environmental and economic outcomes presented here represent a baseline scenario rather than an absolute projection. Specifically, industrial-scale

systems could achieve greater efficiency and lower energy consumption per unit, potentially reducing both environmental impact and costs. Furthermore, given that energy consumption plays a significant role, especially at higher print resolutions and longer printing times, the use of different energy mixes (e.g. renewable versus fossil fuels) could significantly shift the balance between the analysed routes. Finally, the current simplified cost structure captures the primary cost drivers but excludes macroeconomic fluctuations. Future studies should explore these aspects further through dedicated sensitivity analyses to systematically quantify the impact of these variables. Again, future research should also explore the feasibility of using mechanically and chemically recycled polymers in 3D printing to determine their effectiveness in reducing environmental impacts.

The economic model adopted in this study represents a simplified approach to comparing cost trends across materials and print resolutions and the analysis does not follow the Life Cycle Costing approach. Some cost components, such as labour and the maintenance variability, were not explicitly included as they are highly context-dependent and outside the scope of this comparative analysis. The failure rate was assumed constant across all scenarios to ensure consistency, while repair costs were considered an average contribution. Furthermore, the cost per layer indicator should be interpreted as a comparative metric rather than a direct representation of economic value. These simplifications introduce limitations, and future research should include sensitivity analyses and more detailed cost models to improve the robustness of economic evaluations in AM.

Conclusions

This study highlights the importance of material selection and printing settings in determining the sustainability of 3D printing by integrating the LCA methodology with an EA. The analysis aimed to compare materials produced with different polymers but with the same geometry, not providing indications on general material sustainability performance but only on the modelled manufacturing conditions. The environmental results seemed to show that impacts increase significantly with printing resolution, primarily due to the rise in printing time and associated electricity consumption. GW ranged from 4.80E-02 kg CO₂ eq for PLA in DM to 1.51E-01 kg CO₂ eq for ABS in UM, confirming the strong influence of process parameters on environmental performance. Regarding the EA, FLEX appeared to be the most expensive material to print, with a cost ranging from 2.02 to 2.99 EUR per item (increase of around 48%), while PLA was the most cost-effective material, with a cost ranging from 0.70 to 2.57 EUR (increase of around 270%) per item. Considering the layer cost, FLEX ranged from 0.60 to 0.15

EUR per mm (decrease of around 75%) for DM and UM settings, respectively, while PLA ranged from 0.21 to 0.13 EUR per mm (decrease of around 38%). In conclusion, the results indicate that both material selection and process parameters influence environmental and economic performance. PETG and PLA appeared to exhibit the lowest environmental impacts compared to other materials, while PLA offers a favourable balance between cost and sustainability. However, these findings should be interpreted within the specific assumptions and system boundaries of the study, as factors such as electricity mix, process scale, and material properties may influence the results. Due to the lack of a systematic sensitivity analysis, the results should not be widely generalised, as alterations in the electricity mix, processing intensity, or scaling effects could mitigate these impacts. This research contributes to the scientific literature by proposing a new perspective on evaluating the sustainability of 3D printing materials through the synergy between LCA and EA. This study highlights the need for decision-makers, researchers, and industrial stakeholders to adopt a holistic approach that considers both environmental impacts and economic analysis when selecting materials and settings for 3D printing.

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Data availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no conflicts of interest.

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