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Research

Evaluating Sustainable Material Choices for 3D-Printed Pharmaceuticals in the UK Manufacturing Sector: A Comprehensive Review

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Abstract

The emergence of three-dimensional (3D) printing has transformed pharmaceutical development by enabling personalised, flexible, and digitally controlled manufacturing workflows. As the United Kingdom advances toward greener production models and precision medicine, material selection for pharmaceutical fused deposition modelling (FDM) has become a critical determinant of both product performance and environmental sustainability. This review examines the sustainability, functional suitability, and regulatory implications of three key filament classes polylactic acid (PLA), polyvinyl alcohol (PVA), and cellulose-based materials within the context of UK pharmaceutical manufacturing. Drawing on scientific evidence and qualitative insights from industry practitioners and academic researchers, the review evaluates each material's printability, biocompatibility, environmental impact, drug-polymer compatibility, and operational feasibility. PLA and cellulose-based filaments offer favourable biodegradable and renewable profiles, whereas PVA remains the most pharmaceutically versatile but presents environmental burdens. The analysis highlights the need for life-cycle assessment frameworks, material innovation, and regulatory alignment to support sustainable 3D-printed medicines. Recommendations are provided to guide UK manufacturers, policymakers, and pharmaceutical scientists toward responsible material choices that balance performance, safety, and environmental stewardship.

Keywords: 3D printing; sustainable materials; FDM; PLA; PVA; cellulose; pharmaceutical manufacturing; UK; additive manufacturing; biodegradable polymers.

1. INTRODUCTION

Three-dimensional (3D) printing also known as additive manufacturing has rapidly transitioned from a prototyping tool into a transformative technology in modern pharmaceutical production. By enabling precise control over dosage form geometry, internal structure, and drug distribution, 3D printing supports the

development of personalised medicines, on-demand production models, and new drug-release architectures that are difficult or impossible to achieve through conventional manufacturing approaches (1,2). Within the United Kingdom, interest in pharmaceutical 3D printing has expanded significantly, driven by NHS digital transformation initiatives, academic research networks, and industrial strategies targeting both personalised therapeutics and sustainable, low-waste manufacturing systems (3).

Among 3D printing technologies, fused deposition modelling (FDM) stands out as the most widely explored in pharmaceutical research. FDM relies on thermoplastic filaments that are heated, softened, and deposited layer by layer to form a solid structure (4,5). The success of this process depends heavily on the selection of an appropriate filament material. A pharmaceutical filament must not only support precise printing but must also demonstrate compatibility with active pharmaceutical ingredients (APIs), maintain structural integrity, ensure patient safety, and critically align with environmental sustainability goals. As the UK moves toward Net Zero commitments, sustainable material choices are becoming increasingly relevant to manufacturers, regulators, and healthcare organisations (6).

Three major classes of polymeric filaments dominate current pharmaceutical FDM research**:** polylactic acid (PLA), polyvinyl alcohol (PVA), and cellulose-based materials**.** Each offers unique advantages but also presents limitations that influence its suitability for large-scale or clinical-grade printing. PLA and cellulose are often promoted as environmentally favourable due to their biodegradability and biobased origins (7,8), whereas PVA is widely regarded as the most pharmaceutically versatile due to its water solubility and long-standing recognition as a pharmaceutical excipient (9). However, the environmental persistence of PVA and its contribution to aquatic micro-residue pollution challenge its acceptability within sustainable manufacturing frameworks (10).

In the context of UK pharmaceutical operations, sustainability concerns are becoming increasingly intertwined with material selection decisions. The NHS's "Net Zero" strategy encourages greener supply chains and low-carbon production models, placing pressure on manufacturers to adopt environmentally responsible materials (6). Simultaneously, the growth of decentralised and on-demand pharmaceutical printing particularly within hospital settings requires materials that are not only sustainable but also operable under variable environmental conditions. Evidence from industry interviews conducted in the dissertation *Material Selection and Sustainability in 3D Printing for Pharmaceutical Manufacturing in the UK* highlights substantial challenges faced by UK practitioners, including PVA's moisture sensitivity, PLA's brittleness, and printability issues associated with cellulose-based filaments.

Furthermore, the concept of sustainability in pharmaceutical manufacturing extends beyond biodegradability alone. A holistic evaluation must consider:

- feedstock origin and renewability**,**
- energy consumption during printing**,**
- material toxicity and end-of-life fate**,**
- waste generation and recyclability**,** and
- compliance with emerging environmental regulations **(11,12).**

Life-cycle assessment (LCA) frameworks are increasingly recommended by regulatory bodies and sustainability auditors, yet standardised LCA applications for pharmaceutical 3D printing materials remain limited (13). This gap poses challenges for UK companies attempting to evaluate the environmental performance of filament options in a meaningful and comparable way.

PLA is frequently positioned as the environmentally responsible default due to its renewable agricultural feedstock origins and its ability to biodegrade under industrial composting conditions (7). Its low carbon footprint relative to petroleum-based plastics makes it attractive for sustainability-focused applications. However, PLA's mechanical brittleness, high extrusion temperatures, and limited compatibility with hydrophilic APIs constrain its pharmaceutical utility (14). Thus, while PLA may support environmentally aligned objectives, it may not consistently deliver the performance required for complex patient-centric dosage forms.

PVA occupies the opposite end of the spectrum. It is widely viewed as the most pharmaceutically useful filament due to its solubility, printability, and established safety profile (9,15). PVA supports immediate-release, modified-release, and high-drug-load formulations, making it the preferred material for clinical or near-clinical FDM research. Despite these advantages, PVA's environmental profile is poor: it dissolves in water but does not biodegrade effectively, contributing to persistent micro-pollution in wastewater systems (10). For UK manufacturers aiming to reduce environmental burden, this represents a major drawback and may conflict with emerging environmental standards.

Cellulose-based materials present a promising middle ground. Derived from renewable biomass such as wood pulp or cotton, cellulose is inherently biodegradable, non-toxic, and abundant (8). These properties align closely

with UK sustainability objectives and global interest in renewable bioeconomy-based polymers. However, cellulose's lack of natural thermoplasticity imposes technical constraints; extensive modification or blending is required to make it suitable for extrusion or FDM printing (16). Even then, print performance can be inconsistent, leading to nozzle clogging and weak mechanical structures—limitations confirmed in UK laboratory experiences.

Given the competing demands of pharmaceutical performance and environmental sustainability, selecting the optimal filament for pharmaceutical 3D printing in the UK requires a careful balance. The decision landscape intersects technical feasibility, regulatory approval, drug–polymer interactions, operational constraints, and sustainability metrics. Despite growing interest, the absence of standardised guidance from the MHRA or international regulatory agencies hampers widespread adoption and material optimisation efforts (17).

Thus, this review aims to systematically evaluate PLA, PVA, and cellulose-based filaments with a specific focus on sustainability and applicability within the UK pharmaceutical manufacturing sector. Through a combination of peer-reviewed evidence and practitioner insights, it provides a detailed assessment of printability, drug-polymer compatibility, environmental performance, regulatory status, and operational practicality. By consolidating these dimensions, the review supports UK manufacturers, researchers, and policymakers in making informed, sustainability-aligned material decisions as the pharmaceutical sector transitions toward digital and eco-efficient production paradigms.

2. DISCUSSIONS

Material selection determines the feasibility, performance, and sustainability of pharmaceutical fused deposition modelling (FDM). In the UK, where Net Zero manufacturing goals, NHS sustainability priorities, and digital pharmaceutical innovation intersect, the choice of filament materials such as PLA, PVA, and cellulose-based polymers requires a multidimensional assessment (18). This section evaluates each material across printability, drug–polymer compatibility, environmental sustainability, regulatory status, and practical manufacturability within UK settings.

2.1 Printability and Mechanical Performance

Printability directly affects the reliability, efficiency, and repeatability of FDM-based pharmaceutical production. PLA, PVA, and cellulose derivatives differ substantially in thermal transitions, melt flow behaviour, and mechanical stability, shaping their suitability for drug-loaded dosage forms.

2.1.1 PLA

PLA is recognised for its excellent dimensional stability and smooth extrusion due to its low shrinkage, semi-crystalline structure, and moderate melting temperature (19). Its rigidity enables precise manufacture of oral tablets, implantable structures, and fixed-dose combination devices. However, its brittleness can lead to filament snapping, especially under long production cycles or suboptimal storage conditions—a challenge repeatedly reported by UK practitioners in the dissertation. In addition, PLA's hydrophobicity limits its use with hydrophilic APIs, and its processing temperatures can degrade thermolabile drugs (20).

2.1.2 PVA

PVA demonstrates excellent layer adhesion, consistent melt flow, and mechanical flexibility, making it highly suitable for immediate-release and modular dosage forms (21). Its water solubility further supports dissolution-controlled architectures and multi-drug polypills. However, PVA is extremely hygroscopic; filament swelling, irregular diameter changes, and moisture-induced nozzle blockages remain major operational constraints (22). UK laboratory insights emphasise that humidity instability frequently compromises print reliability in non climate-controlled environments.

2.1.3 Cellulose-Based Materials

Cellulose and its derivatives align well with sustainability and biocompatibility requirements, but their printability remains limited (23). Native cellulose lacks thermoplasticity, requiring plasticisers or chemical modification such as acetylation. Even with modification, cellulose filaments often exhibit inconsistent melt viscosity, weak interlayer bonding, and high nozzle clogging frequency. These challenges currently restrict large-scale or clinical-grade use in the UK, despite growing interest in nanocellulose composites and hybrid bio-based blends.

Table 1. Comparative Evaluation of Sustainable Filament Materials (PLA, PVA, Cellulose) for Pharmaceutical FDM

Parameter	PLA	PVA	Cellulose-Based Materials
Source	Renewable (corn, sugarcane)	Synthetic	Renewable (wood pulp, cotton)
Biodegradability	Industrially compostable	Poor biodegradability; dissolves but persists	Fully biodegradable
Environmental Impact	Low carbon footprint	High water and energy usage; micro-residue risk	Very low; circular bioeconomy compatible
Printability	Stable extrusion, brittle	Excellent adhesion, moisture-sensitive	Inconsistent melt flow; clogging
API Compatibility	Hydrophobic APIs; sustained-release	Hydrophilic APIs; high drug loading	Broad compatibility; mucoadhesive
Mechanical Strength	Rigid, brittle	Flexible, strong adhesion	Varies by derivative
Regulatory Status	Recognised for implants	Strong regulatory acceptance	Established for excipients; limited FDM guidance
Suitability for UK Manufacturing	Good for prototypes & eco-aligned products	Best for clinical formulations	Best sustainability potential; printability barriers

2.2 Drug–Polymer Compatibility and Release Behaviour

Drug compatibility influences dosage uniformity, drug stability, and therapeutic performance. PLA, PVA, and cellulose-based materials exhibit distinct drug–polymer interactions that define their potential roles in UK pharmaceutical manufacturing.

PLA

PLA's hydrophobic matrix is well suited for hydrophobic or moderately lipophilic APIs, supporting sustained-release implants and long-acting delivery systems (24). However, changes in crystallinity during printing may alter drug-release kinetics, requiring strict thermal control during manufacturing.

PVA

PVA is the most pharmaceutically versatile among the three materials due to its well-established excipient status and compatibility with numerous hydrophilic APIs (25). Its solubility enables design of rapid-release tablets, microchannelled dosage forms, and personalised drug combinations. PVA's ability to form uniform drug dispersions supports precision dosing an important requirement in personalised medicine initiatives in the UK.

Cellulose-Based Materials

Cellulose derivatives, widely used in conventional oral dosage forms, offer excellent mucoadhesive properties, biocompatibility, and broad API compatibility (26). Their print-related structural inconsistencies, however, can lead to variable drug-release behaviour unless advanced modification methods are applied.

2.3 Environmental Sustainability

Sustainability is increasingly central to UK pharmaceutical manufacturing due to legislative and NHS-driven commitments to carbon reduction and waste minimisation (6). Material selection therefore requires lifecycle thinking, including feedstock origin, biodegradability, and end-of-life impacts.

PLA

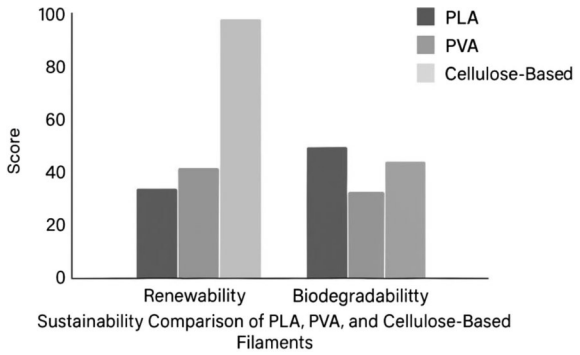
PLA performs strongly in sustainability assessments due to its renewable biomass origins, industrial compostability, and comparatively low carbon footprint (7). As UK pharmaceutical organisations adopt lifecycle assessments, PLA's environmental advantages make it a favourable candidate despite limitations in API compatibility.

PVA

PVA dissolves readily in water but does *not* biodegrade effectively, leading to accumulation of micro-residues in aquatic systems (10). This characteristic conflicts with the UK's broader environmental priorities. High water consumption during PVA dissolution also increases its environmental burden.

Cellulose-Based Materials

Cellulose is the most environmentally aligned polymer of the three. It is renewable, biodegradable under natural conditions, and compatible with circular bioeconomy principles (8). For the UK pharmaceutical sector aiming to integrate sustainability metrics into GMP and MHRA-compliant processes, cellulose offers long-term strategic potential—once printability challenges are addressed.



Sustainability Comparison of PLA, PVA, and Cellulose-Based Filaments

2.4 Safety and Regulatory Considerations

Regulatory acceptance remains uneven across these materials.

- **PLA** is widely used in biomedical devices and accepted by EMA and MHRA for certain implantable applications (27).
- **PVA** has the strongest regulatory standing due to its longstanding use as a pharmaceutical excipient in oral and ophthalmic products (28).
- **Cellulose derivatives** (e.g., HPMC, HPC, CA) are recognised excipients, but **cellulose-based FDM filaments** have limited regulatory guidance (29).

For the UK, the absence of MHRA-specific FDM material standards highlights the need for harmonised regulations supporting sustainable material adoption.

2.5 Operational Constraints in UK Manufacturing

Evidence from the dissertation confirms several recurring challenges faced by UK practitioners
Comparative Study of PLA

PVA → severe moisture sensitivity

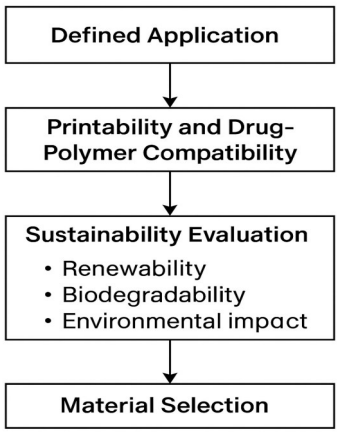
- **PLA** → brittleness and snapping during feeding
- **Cellulose** → frequent nozzle clogging
- **Limited UK suppliers** of pharmaceutical-grade sustainable filaments
- **Lack of workforce training** in polymer science and FDM-specific processing

These constraints underscore the need for improved supply chains, humidity control solutions, and training programmes within the UK manufacturing landscape.

2.6 Future Directions for Sustainable UK Pharmaceutical 3D Printing

- Development of next-generation bio-based materials such as nanocellulose composites
- Creation of PLA–cellulose hybrid filaments optimised for sustainable printing
- Establishment of MHRA sustainability metrics in pharmaceutical additive manufacturing
- Adoption of AI-assisted material selection tools
- Investment in UK-based filament production to reduce import dependencies

These innovations will help align pharmaceutical 3D printing with environmental and clinical priorities.



Material Selection Framework
for Sustainable Pharmaceutical FFDM

3. CONCLUSION

The evaluation of PLA, PVA, and cellulose-based materials demonstrates that sustainable material selection is central to advancing pharmaceutical 3D printing within the UK's evolving manufacturing landscape. PLA offers strong environmental benefits, including a renewable origin and industrial biodegradability, aligning closely with the UK's Net Zero ambitions. However, its limited compatibility with hydrophilic APIs and brittleness restrict its pharmaceutical flexibility. PVA remains the most pharmaceutically adaptable filament due to its solubility, drug-loading versatility, and well-established regulatory acceptance. Yet its poor biodegradability and high moisture sensitivity create significant environmental and operational challenges, particularly for decentralised and hospital-based printing environments.

Cellulose-based materials present the most promising long-term solution, offering outstanding sustainability and biocompatibility. Despite their current printability limitations such as inconsistent melt flow and nozzle clogging ongoing advancements in nanocellulose engineering and modified cellulose derivatives suggest strong potential for future adoption. Practitioner insights from UK settings emphasise the importance of improving filament reliability, expanding local supply chains, and integrating sustainability metrics into regulatory assessments.

Overall, achieving sustainable pharmaceutical 3D printing in the UK requires coordinated progress across materials engineering, regulatory development, and life-cycle assessment. Hybrid bio-based filaments and improved manufacturing standards are likely to play key roles in enabling environmentally responsible, patient-centred additive manufacturing.

REFERENCES

1. Norman J, Madurawe RD, Moore CM, Khan MA, Khairuzzaman A. A new chapter in pharmaceutical manufacturing: 3D-printing. J Pharm Sci. 2017; 106(1):1–10. doi:10.1016/j.xphs.2016.10.001
2. Jamróz W, Szafraniec J, Kurek M, Jachowicz R. 3D printing in pharmaceutical and medical applications: recent achievements and challenges. Pharm Res. 2018; 35(9):176. doi:10.1007/s11095-018-2454-x
3. Trenfield SJ, Awad A, Madla CM, et al. Shaping the future: 3D printing in the pharmaceutical sciences. Pharmaceutics. 2018; 10(2):20. doi:10.3390/pharmaceutics10020020
4. Lee Ventola C. Medical applications for 3D printing: current and projected uses. P T. 2014;39(10):704–11.
5. Goyanes A, Det-Amornrat U, Wang J, et al. 3D scanning and 3D printing as innovative tools for personalized topical drug delivery. J Control Release. 2016;234:41–48. doi:10.1016/j.jconrel.2016.05.034
6. NHS England. Delivering a 'Net Zero' National Health Service. 2020. Available from: https://www.england.nhs.uk/greenernhs/net-zero
7. Auras R, Harte B, Selke S. An overview of polylactides as packaging materials. Macromol Biosci. 2004;4(9):835–864. doi:10.1002/mabi.200400043

8. Thomas B, Raj MC, Athira KB, et al. Nanocellulose, a versatile green platform: from biosources to materials and their applications. Carbohydr Polym. 2018; 198:329–356. doi:10.1016/j.carbpol.2018.06.089
9. Siepmann J, Peppas NA. Modeling of drug release from delivery systems based on HPMC. Adv Drug Deliv Rev. 2001; 48:139–157. doi:10.1016/S0169-409X(01)00112-0
10. Zolnai Z, et al. Environmental persistence of PVA. J Environ Chem Eng. 2021; 9(4):105–117. doi:10.1016/j.jece.2021.105117
11. Hottle TA, Bilec MM, Landis AE. Life cycle assessment of PLA, PP, and PET. J Clean Prod. 2017;164: 1195–1205. doi:10.1016/j.jclepro.2017.07.016
12. Rawlings R, et al. Sustainable materials in pharmaceutical manufacturing: a review. Green Chem Lett Rev. 2020; 13(3):256–270. doi:10.1080/17518253.2020.1780540
13. Cucuzzella C, Salvia G. Assessing sustainability in product design. J Clean Prod. 2018; 182: 113–124.
14. Farah S, Anderson DG, Langer R. Physical and mechanical properties of PLA. Adv Drug Deliv Rev. 2016; 107: 367–392.
15. Kolakovic R, Laaksonen T, Peltonen L, et al. Spray-dried PVA for drug delivery. Eur J Pharm Sci. 2013;50(3–4):312–322.
16. Agarwal UP. Chemical modification of cellulose. Cellulose. 2019; 26: 107–132.
17. MHRA. Guidance on 3D printing of medical products. 2021. Available from: https://www.gov.uk/mhra
18. Algahtani MS, Mohammed AA, Ahmad J. 3D printing in formulation, development and industrial application: a review. Drug Dev Ind Pharm. 2021; 47(1):1–15. doi:10.1080/03639045.2020.1840637
19. Chia HN, Wu BM. Recent advances in 3D printing of biomaterials. J Biol Eng. 2015; 9:4. doi:10.1186/s13036-015-0001-4
20. Melocchi A, Uboldi M, Parietti F, et al. Hot-melt extrusion and 3D printing for pharmaceuticals. Drug Dev Ind Pharm. 2019;45(4): 1018–1030.
21. Goyanes A, Buanz A, Basit AW, Gaisford S. Fused-filament fabrication 3D printing for tablets. Int J Pharm. 2014; 476:88–92.
22. Strain I, Wu W, Bodratti AM. Moisture effects on PVA filament. J Appl Polym Sci. 2020; 137: 49522.
23. Klemm D, Heublein B, Fink HP, Bohn A. Cellulose biocomposites. Angew Chem Int Ed. 2005; 44:3358–3393.
24. Pitt CG. Controlled release from PLA-based devices. J Control Release. 1990; 16:23–30.
25. Goyanes A et al. FDM printing for personalized medicines. Int J Pharm. 2016; 499:157–167.
26. Rowe RC, Sheskey PJ, Quinn ME. Handbook of Pharmaceutical Excipients. 6th ed. London: Pharmaceutical Press; 2009.
27. Middleton JC, Tipton AJ. Synthetic biodegradable polymers. Biomaterials. 2000; 21:2335–2346.
28. CP Kelco. PVA excipient safety profile. Technical Monograph. 2019.
29. Nair SS, Zhu JY, Deng Y. Cellulose nanofibrils for drug delivery. Carbohydr Polym. 2014; 112:640–649.