

The Role and Selection Criteria of Binder Materials for Sustainable Filaments Used in Additive Manufacturing

Norbert Simon, Eszter Kókai*

Széchenyi István University, Department of Applied Sustainability, Egyetem tér 1, 9026 Győr, Hungary
kokai.eszter@sze.hu

The growing adoption of additive manufacturing increases the need for filament materials that satisfy both technical and environmental requirements. In Fused Filament Fabrication (FFF), the binder system in metal–polymer filaments plays a key role in determining environmental impact and processing quality. This review analyses potential binder materials for FFF-based metal additive manufacturing, focusing on how their properties influence printability, thermal stability, debinding behaviour, and the mechanical performance of green parts. Comparative data on thermal and mechanical characteristics are presented for conventional and bio-based polymers. The candidate binder materials show melting points between 60 °C and 200 °C and degradation onset from 240 °C to 340 °C, defining their usability range. PLA provides the highest strength, while PCL and TPS offer flexibility and low-temperature processing. PVB/PEG ensures rigidity and clean debinding, and HPMC enables easy water removal. PLA, TPS, and HPMC exhibit the best sustainability profile due to their bio-based origin. A similar comparative analysis has not been reported in the literature.

1. Introduction

Fused Filament Fabrication (FFF) is an additive manufacturing method where polymer or metal–polymer composite filaments are extruded layer by layer (Figure 1). Complex shapes often need temporary supports, which must be removed without damaging the part. Supports are typically broken off mechanically or dissolved in a solvent, but these methods can pose environmental and health risks.

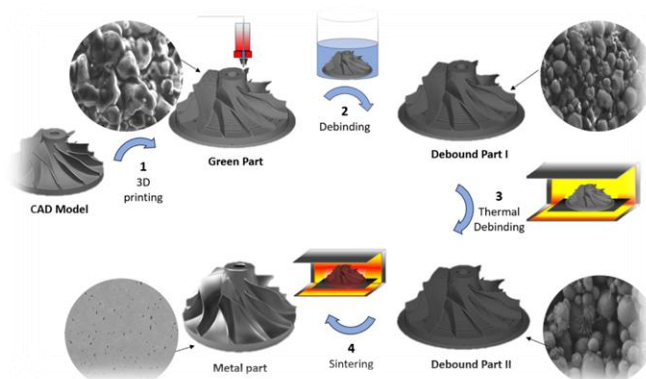


Figure 1: Schematic representation of the metal FFF process (Jacob et al., 2024)

Water-soluble supports offer a cleaner alternative, reducing the need for toxic solvents or high-temperature burning. FFF is widely used not only for plastics but also for composites with metal or ceramic particles, where the polymer works as a binder. After printing, the binder is removed (debinding) and the part is sintered to achieve final strength. The choice of binder is critical, as it affects not only print quality and mechanical integrity but also the environmental footprint of the process (Vaes and Van Puyvelde, 2021). Recent developments in

binder and support formulations have focused on balancing printability, solubility, and biodegradability, with research exploring both petroleum-derived and bio-based polymers (Bankapalli and Gupta, 2023). Advances in water-soluble and partially water-soluble systems aim to minimize hazardous waste generation, while industrial binder systems are being optimized for higher thermal stability and cleaner debinding stages. As additive manufacturing continues to expand into high-performance applications, the demand for sustainable, high-functionality support and binder materials is expected to grow, driving further innovation in the field. In recent years, the development of bio-based and recycled feedstocks for FFF has gained attention, aiming to reduce environmental impact while maintaining print quality. Studies have demonstrated the feasibility of producing filaments from post-consumer bioplastic waste (Patti et al., 2022) and the potential of controlling 3D printing parameters to lower energy consumption without compromising part performance (Patti et al., 2023). Unlike previous reviews focusing solely on printability or material properties, this work provides a comparative framework linking thermal, solubility, and degradation parameters to environmental performance. Previous reviews have addressed the role of materials and binders in extrusion-based additive manufacturing. Vaes and Van Puyvelde (2021) examined how the crystallinity and viscosity of semi-crystalline feedstocks influence printability and part quality. Jacob et al. (2024) focused on metal FFF processes, highlighting binder functions in feedstock design and sintering. Bankapalli and Gupta (2023) discussed filament fabrication, debinding, and sintering steps in metal additive manufacturing, with an emphasis on process optimisation rather than binder selection or sustainability.

2. Comparison of binder solubility

2.1. Water-soluble binders: PVA, BVOH

Polyvinyl alcohol (PVA) is a long-established water-soluble polymer for FFF printing. It dissolves quickly in warm water (40–70 °C) without leaving toxic residues, and is biodegradable under suitable conditions (Chiellini et al., 2003). In solid form, it provides stable supports, though it is moisture-sensitive and requires drying before printing (Tacx et al., 2000). It is compatible with low-temperature materials such as polylactic acid (PLA) and acrylonitril-butadiene-styrene copolymer (ABS). Butanediol vinyl alcohol copolymer (BVOH) offers similar water solubility to PVA but with improved printability and storage stability. It dissolves particularly fast in mildly alkaline solutions and is less sensitive to ambient humidity (Paśnikowska-Lukaszuk et al., 2023). BVOH adheres well to PLA and polyethylene terephthalate glycol (PETG) and offers higher thermal stability, making it suitable for industrial use.

2.2. Water-soluble and partially water-soluble binders: PEG, PVB/PEG blends, PVA+PEG blends, HPMC

Polyethylene glycol (PEG) is a low-melting, water-soluble polyether commonly used in binder systems as a flexible, leachable component that enables partial binder removal without flammable solvents (Nötzel and Hanemann, 2020). In metal and ceramic filaments, water leaching of PEG creates pores that facilitate subsequent thermal debinding. The polyvinyl butyral (PVB)/PEG blend, widely applied in metal injection molding and FFF, combines PVB's mechanical strength with PEG's water-solubility, enabling a two-step debinding process that reduces solvent use and supports crack-free sintering (Eickhoff et al., 2024). While PVB dissolves in ethanol, it is petroleum-based and non-compostable, requiring wastewater treatment after solvent debinding. The PVA+PEG blend operates similarly but is fully water-soluble. PEG plasticizes PVA, improving flexibility, moisture resistance, and mechanical stability (Labus et al., 2023). The blend is inexpensive, biodegradable, and easy to remove in water, though extrusion requires temperature control due to PVA degradation above ~200 °C. Hydroxypropyl methylcellulose (HPMC) is a plant-derived, water-soluble polymer that gels upon heating (Cheng et al., 2020). It is biodegradable, adheres well to model materials, and can be easily rinsed away, making it a promising sustainable support material for future filament-based FFF applications.

2.3. Non-water-soluble binders: PLA, PCL, TPS

PLA is one of the most widely used FFF materials. Produced from renewable sources such as corn starch or sugarcane, it offers a lower carbon footprint than petroleum-based plastics (Cheng et al., 2020). PLA's role in reducing greenhouse gas emissions through renewable sourcing has been widely reviewed (Mosomi et al., 2024). Life cycle assessments further confirm its lower environmental impact compared to fossil-based polymers (Ghomi et al., 2021). Its potential applications in advanced biopolymer systems have also been discussed (Casalini et al., 2019). It is compostable under industrial conditions (50–60 °C, high humidity) but degrades more slowly in home composting or natural environments. PLA is not water-soluble but dissolves in some organic solvents, including dichloromethane and chloroform. With a low melting point (~150–160 °C) and minimal shrinkage, PLA is highly printable and suitable for both beginners and professionals. It provides good stiffness and tensile strength but lower toughness compared to ABS or PCL. As a support material, PLA is typically used

in breakaway form; while less practical than water-soluble options, it remains preferable to non-degradable supports due to its recyclability and compostability. Polycaprolactone (PCL) is a flexible, biodegradable polyester with a low melting point (~60 °C), enabling low-temperature processing (Boucher, 2020). Its mechanical performance and suitability for specific applications, such as medical and bio-prototyping uses, have also been demonstrated (Popescu et al., 2023). It is biocompatible and slowly degrades over months or years, making it useful in medical and bio-prototyping applications. PCL is insoluble in water but dissolves in organic solvents such as chloroform and dichloromethane. It prints with minimal warping and can be blended with other materials, although pure PCL filaments are less common. Thermoplastic starch (TPS) is an inexpensive, biodegradable polymer derived from plant starches and plasticizers (Dominici et al., 2025). The processing and performance of TPS blends for FFF have been extensively investigated, highlighting their potential for improved compostability and mechanical performance (Ju et al., 2022). The integration of food waste into TPS-based formulations has also been explored as a strategy to enhance sustainability (Wang et al., 2024). It processes at 120–170 °C but is brittle and moisture-sensitive, so it is often blended with PLA or polybutylene adipate terephthalate (PBAT) to improve mechanical properties and compostability. PLA–TPS blends are fully bio-based and degrade faster than pure PLA, even in home composting. TPS swells in water and degrades quickly in hot water or with enzymes, offering potential as a temporary support material.

2.4. Stratasys® SR-30, SR-100, SR-110 support materials

The SR-series (SR-30, SR-100, SR-110) is a proprietary Stratasys® copolymer for industrial Fused Deposition Modeling (FDM by Stratasys®), designed to work with high-temperature materials such as ABS, PC, and nylon (Stratasys GmbH, 2025). They dissolve in mildly alkaline heated solutions, enabling automated support removal. SR-30 is optimized for ABS and ASA; it dissolves in ~70 °C alkaline baths (<2 % NaOH) with detergent additives, offering a thermal expansion profile closely matching ABS for high surface quality. SR-100 is for PC, with high softening temperature and strong adhesion to withstand ~280–300 °C extrusion. SR-110 is for PC-ABS and nylons, combining high heat resistance with alkaline solubility. Removal typically uses heated, circulating NaOH-based systems such as Stratasys WaveWash. While efficient, the process generates alkaline waste that must be neutralized and treated. The biodegradability of the dissolved residue is unclear. SR materials are less environmentally friendly than simple water-soluble supports like PVA or BVOH, but they deliver superior stability, precision, and reliability in demanding industrial applications.

3. Thermal properties comparison of binder materials (solubility, melting temperature, printing temperature, and thermal degradation temperature)

In Table 1, various support and binder materials (e.g., PVA, BVOH, PEG, PLA, PCL, Stratasys SR-30, SR-100, SR-110, etc.) are compared in terms of their solubility, melting temperature, printing temperature, and thermal degradation temperature. From a solubility standpoint, PVA and BVOH stand out due to their water solubility, in contrast to materials like PCL and PEG, which dissolve only in organic solvents. The typical printing temperature range for most materials lies between 200–225 °C, whereas Stratasys support materials require significantly higher temperatures, generally within the 230–270 °C range. The degradation temperatures of the listed materials vary between 240 °C and 340 °C. The thermal data in Table 1 originate from different studies using distinct measurement techniques (e.g., DSC, TGA) and should be regarded as representative values rather than directly comparable. Nevertheless, they provide useful guidance for assessing the processability and thermal stability of the binders. Among the water-soluble polymers, PVA displays a melting temperature around 200 °C and begins to thermally degrade near 239 °C (Chiellini et al., 2003). BVOH melts at approximately 175 °C and shows stable printability up to about 250 °C (Paśnikowska-Łukaszuk et al., 2023). PEG exhibits a much lower melting point of around 60 °C, offering excellent flowability but limited thermal resistance (Labus et al., 2023). PCL also melts near 60 °C, providing easy low-temperature processability while starting to degrade between 290 °C and 320 °C (Boucher, 2020). PLA melts within the 150–170 °C range and maintains structural integrity up to about 290 °C (Ghomi et al., 2021). TPS softens between 100 °C and 130 °C, with degradation typically occurring around 305 °C (Ju et al., 2022). PVB/PEG systems, though amorphous, show good thermal stability up to approximately 260 °C, making them suitable for metal or ceramic feedstocks that require high green-part integrity (Eickhoff et al., 2024). HPMC behaves differently, forming a thermogel between 50 °C and 70 °C instead of melting, which restricts its use to low-temperature paste extrusion processes (Cheng et al., 2020). In contrast, Stratasys SR-series materials operate at higher temperature ranges: SR-30 prints at about 230–240 °C, while SR-100 and SR-110 are suitable for 260–270 °C, demonstrating the highest thermal resistance among the studied materials (Stratasys GmbH, 2025).

Table 1: Comparison of selected polymers in terms of solubility, printability, and degradation

Material	Solvent	Solubility temperature	Melting temperature	Printing temperature	Degradation temperature	Reference
PVA	Water-soluble	Soluble at room temperature (dissolves faster in warm water, e.g., 40–70 °C)	~200 °C	~215 °C	~239 °C	Chiellini et al., 2003
BVOH	Water-soluble	Soluble at room temperature (dissolves faster in warm water, e.g., 40–60 °C)	~175 °C (T _m)	~225 °C	~250 °C	Paśnikowska-Lukaszuk et al., 2023
PEG	Water Highly soluble (hydrophilic)	Soluble at room temperature (rapid water solubility)	~60 °C	Not used on its own For FDM applications	~340 °C	Labus et al., 2023
PVB+PEG	Alcohols/acetates (e.g., ethanol, isopropanol; PEG component is also water-soluble)	Slow dissolution at room temperature (faster in ethanol; IPA also effective). Heating accelerates dissolution.	No sharp melting point PVB is amorphous (T _g ≈ 60 °C); PEG ~50–60 °C	~220 °C	~260 °C	Eickhoff et al., 2024
PVA+PEG	Water Both components are water-soluble	Soluble at room temperature (PEG accelerates water uptake)	No sharp melting point PVA ~187–195 °C; PEG ~50–60 °C	~180–200 °C	~310 °C	Labus et al., 2023
HPMC	Water Soluble in cold water; not in hot water (forms gel upon heating)	~20 °C (soluble in cold water) Thermogelation at ~50–70 °C (gel formation upon heating)	No crystalline melting T _g ~178 °C	~175–180 °C	~200 °C	Cheng et al., 2020
PLA	Organic solvents (e.g., chloroform, dichloromethane, THF dissolve it)	At room temperature (in organic solvent)	~150–170 °C	~190–220 °C	~290 °C	Rezvani Ghomi et al., 2021
PCL	Organic solvents (e.g., chloroform, dichloromethane, THF dissolve it)	Soluble at room temperature (slowly; fully dissolves in ~24 h in dichloromethane; heating accelerates dissolution) Easily soluble in warm water (~40–60 °C; rapid dissolution)	~60 °C	~100 °C	~290 °C (initial) ~320 °C (main decomposition)	Boucher, 2020; Popescu et al., 2023
TPS	Water Highly soluble (hydrophilic)	Swells and partially dissolves at room temperature	No sharp melting point (softens at ~100–130 °C)	~140 °C	~305 °C	Ju et al., 2022; Wang et al., 2024
SR30 (Stratasys® support filament)	Alkaline aqueous solution (NaOH-based, e.g., Stratasys® Ecoworks)	~70 °C (rapid dissolution)	~200 °C (estimated, PVA-based composition)	~230–240 °C (co-extruded with ABS, FDM process)	~239 °C (estimated onset of decomposition, based on PVA component)	Stratasys GmbH, 2025
SR100 (Stratasys®, for PC)	Alkaline solution (NaOH, mild, ~pH 10)	~70 °C (circulated warm aqueous solution recommended)	N/A*	~300 °C (co-extruded with PC model material)	N/A*	Stratasys GmbH, 2025
SR110 (Stratasys®, for PC-ABS/nylon)	Alkaline solution (NaOH, mild)	~70 °C (recommended dissolution bath temperature)	N/A*	~260–270 °C (printing range for PC-ABS, Nylon 12)	N/A*	Stratasys GmbH, 2025

* N/A — not available in literature

4. Mechanical properties comparison of binders

Since the measurement protocols differ—such as specimen geometry, testing conditions, and whether the data refer to neat polymers, printed parts, or filled feedstocks—the mechanical results cannot be directly compared. However, the reported values provide useful guidance on the basic mechanical behaviour of each binder material, supporting their practical selection for specific FFF applications. The representative data summarised in Table 2 illustrate these indicative property ranges. Among the studied binders, PLA shows the highest stiffness and strength (15–150 MPa) (Ghomi et al., 2021), while PCL is softer and more ductile (~18 MPa) (Popescu et al., 2023). PVB/PEG systems offer adjustable rigidity from below 500 MPa to about 1.4 GPa, suitable for metal or ceramic feedstocks (Eickhoff et al., 2024). HPMC forms a soft hydrogel (~3 kPa) for removable supports (Cheng et al., 2020). TPS blends improve toughness and flexibility while remaining bio-based (Ju et al., 2022).

Table 2: Representative mechanical properties for candidate binders used in FFF contexts.

Material	Test condition	Typical value(s)	Reference
PLA (neat/printed)	Tensile strength (printed parts; grade and process dependent)	~15.5–150 MPa	Rezvani Ghomi et al., 2021
PCL (printed)	Ultimate tensile strength (dog-bone, printed orthosis geometry)	~18 MPa	Popescu et al., 2023
PVB/PEG metal-filled feedstock (binder metrics)	Storage modulus at 25 °C (DMA of 60 vol% Ti-6Al-4V filaments)	“Flexible” formulations: < 500 MPa; “Rigid” formulations: ≈ 1400 MPa	Eickhoff et al., 2024
HPMC (support paste)	Storage modulus G' (12 wt% hydrogel, 1 rad*s ⁻¹)	~3.1 kPa	Cheng et al., 2020
TPS blends (PLS/PBAT/TPS)	Effect of chain extender on toughness (printed filaments)	+113 % elongation at break; +190 % impact strength	Ju et al., 2022

5. Printability and debinding behaviour

Printability in FFF depends mainly on the binder's thermal and rheological behaviour. Materials melting between 180–220 °C, such as PVA, BVOH, and PLA, provide stable extrusion and good layer adhesion (Chiellini et al., 2003). BVOH shows slightly better process stability and faster dissolution (Paśnikowska-Łukaszuk et al., 2023), while PLA offers low warping and consistent print quality (Rezvani Ghomi et al., 2021). Low-melting binders like PEG and PCL allow low-temperature processing but yield parts with reduced strength and accuracy (Labus et al., 2023; Popescu et al., 2023). Debinding mainly depends on binder solubility and degradation temperature. Water-soluble systems such as PVA and PEG blends allow gradual removal in warm water, minimising cracking and preserving shape (Chiellini et al., 2003; Labus et al., 2023). BVOH dissolves efficiently in neutral or alkaline water, maintaining dimensional stability (Paśnikowska-Łukaszuk et al., 2023). In hybrid systems like PVB/PEG, PEG leaches out first, forming porosity for clean thermal removal of PVB, which provides rigidity up to ~260 °C (Eickhoff et al., 2024).

6. Environmental Assessment

The environmental performance of binder materials in FFF depends on their origin, processing, and disposal. Bio-based polymers such as PLA and TPS offer clear sustainability advantages over petroleum-based materials. PLA has a lower carbon footprint due to renewable feedstocks, while TPS provides full biodegradability and faster composting when blended with PLA or PBAT (Wang et al., 2024; Ju et al., 2022). Water-soluble binders like PVA, BVOH, and PEG allow solvent-free removal but produce wastewater that requires treatment (Chiellini et al., 2003; Paśnikowska-Łukaszuk et al., 2023; Labus et al., 2023). PVB/PEG blends ensure high printability and clean debinding, though PVB itself is non-degradable (Eickhoff et al., 2024). PCL degrades slowly and suits biomedical uses (Boucher, 2020), while HPMC is renewable and fully biodegradable (Cheng et al., 2020). Stratasys® SR-series binders remain efficient for printing but require chemical neutralization after alkaline debinding (Stratasys GmbH, 2025).

7. Conclusion

This study compared key binder materials used in FFF-based metal and polymer filaments, linking their thermal, mechanical, and environmental characteristics to printability and debinding behaviour. The results show that binders with melting points between 60–200 °C and degradation onset from 240–340 °C define the main processing window for stable extrusion and clean removal. PVA and BVOH provide reliable printability and water-based removability, while PVB/PEG systems combine mechanical rigidity with efficient two-step

debinding. PLA exhibits the highest strength among biodegradable binders (15–150 MPa), whereas PCL and TPS support flexible, low-temperature processing and improved ductility. HPMC performs well as an easily removable, renewable support material. From an environmental standpoint, bio-based binders such as PLA, TPS, and HPMC show the most favourable sustainability profile due to their renewable origin and biodegradability, while PVB and SR-series materials offer higher thermal stability but require careful waste management. Overall, the findings highlight that optimal binder selection should balance thermal stability, printability, mechanical integrity, and environmental impact to enable more sustainable FFF processing.

References

- Bankapalli N.K., Gupta V., 2023, Filament fabrication and subsequent additive manufacturing, debinding, and sintering for extrusion-based metal additive manufacturing and their applications: A review. *Composites Part B: Engineering*, 264, 110915.
- Boucher D.S., 2020, Solubility parameters and solvent affinities for polycaprolactone: A comparison of methods. *Journal of Applied Polymer Science*, 137(30), 48908.
- Casalini T., Rossi F., Castrovinci A., Perale G., 2019, A perspective on polylactic acid-based polymers use for nanoparticles synthesis and applications. *Frontiers in Bioengineering and Biotechnology*, 7, 259.
- Cheng Y., Shi X., Jiang X., Wang X., Qin H., 2020, Printability of a cellulose derivative for extrusion-based 3D printing: The application on a biodegradable support material. *Frontiers in Materials*, 7, 86.
- Chiellini E., Corti A., D'Antone S., Solaro R., 2003, Biodegradation of poly (vinyl alcohol) based materials. *Progress in Polymer Science*, 28(6), 963–1014.
- Dominici F., Imbriano A., Puglia D., Pagano C., Luzi F., Rafanelli A., Di Michele A., Bonacci F., Ceccarini M.R., Primavilla S., Valiani A., Tensi L., Gutierrez C.L.P., De Melo Barboza R., Viseras C., Ricci M., Perioli L., 2025, Starch-based scaffold produced by FDM 3D printing technique as innovative and biosustainable wound dressing. *European Journal of Pharmaceutics and Biopharmaceutics*, 210, 114698.
- Eickhoff R., Antusch S., Nötzel D., Probost M., Hanemann T., 2024, Development of flexible and partly water-soluble binder systems for metal fused filament fabrication (MF3) of Ti-6Al-4V parts. *Polymers*, 16(17), 2548.
- Ghomi E.R., Khosravi F., Ardahaei A.S., Dai Y., Neisiany R.E., Foroughi F., Wu M., Das O., Ramakirshna S., 2021, The life cycle assessment for polylactic acid (PLA) to make it a low-carbon material. *Polymers*, 13(11), 1854.
- Jacob J., Simunec P.D., Kandjani A.E.Z., Trinchi A., Sola A., 2024, A review of fused filament fabrication of metal parts (metal FFF): Current developments and future challenges. *Technologies*, 12(12), 267.
- Ju Q., Tang Z., Shi H., Zhu Y., Shen Y., Wang T., 2022, Thermoplastic starch based blends as a highly renewable filament for fused deposition modeling 3D printing. *International Journal of Biological Macromolecules*, 219, 175–184.
- Labus N., Kristic J., Matijasevic S., Pavlovic V., 2023, Oxide powder mixture with poly-vinyl alcohol (PVA) and added polyethylene glycol (PEG) as plasticizer. *Science of Sintering*, 55(2), 189–203.
- Mosomi E.K., Olanrewaju O.A., Adeosun S.O., 2024, Pivotal role of polylactide in carbon emission reduction: A comprehensive review. *Engineering Reports*, 6(8), e12909.
- Nötzel D., Hanemann T., 2020, New feedstock system for fused filament fabrication of sintered alumina parts. *Materials*, 13(19), 4412.
- Paśnikowska-Lukaszuk M., Urzędowski A., Wlazło M., Mikušová D., Zaborko J., 2023, Analysis of the solubility of a support filament made of a copolymer of vinyl alcohol and butanediol in aqueous solutions with variable pH. *Journal of Ecological Engineering*, 24(12), 201–207.
- Patti A., Acierno S., Cicala G., Acierno D., 2022, Recycling waste from film packaging to 3D printing applications. *Chemical Engineering Transactions*, 96, 55–60.
- Patti A., Acierno S., Cicala G., Acierno D., 2023, Controlling process variables in 3D printing to limit the energy consumption. *Chemical Engineering Transactions*, 105, 373–378.
- Popescu D., Stochioiu C., Baciú F., Iacob M.C., 2023, 3D-printed polycaprolactone mechanical characterization and suitability assessment for producing wrist–hand orthoses. *Polymers*, 15(3), 507.
- Stratasys GmbH, 2025, FDM support removal. Technical report, <<https://share.google/iog55oOnNOuZ26hHW>>, accessed 17.11.2025.
- Tacx J.C.J.F., Schoffeleers H.M., Brands A.G.M., Teuwen L., 2000, Dissolution behavior and solution properties of polyvinyl alcohol as determined by viscometry and light scattering in DMSO, ethylene glycol and water. *Polymer*, 41(3), 947–957.
- Vaes D., Van Puyvelde P., 2021, Semi-crystalline feedstock for filament-based 3D printing of polymers. *Progress in Polymer Science*, 118, 101411.
- Wang L., Yong L.X., Loo S.C.J., 2024, Utilizing food waste in 3D-printed PLA formulations to achieve sustainable and customizable controlled delivery systems. *ACS Omega*, 9(31), 34140–34150.