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*Short communication*

# Rheology and shape fidelity of poloxamer 407 bioinks

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## Introduction

Semi-solid extrusion 3D printing is increasingly explored for the fabrication of personalized pharmaceutical dosage forms, as it allows for the precise manufacturing of tablets on demand with dosages tailored to an individual's specific physical condition (Zhu et al., 2020). Successful printing requires formulations with appropriate rheological properties to enable filament formation, ensure adequate layer adhesion and maintain structural integrity after deposition.

Poloxamer 407 (P407) is a thermoresponsive polymer widely used to modulate viscosity and viscoelastic behavior in aqueous systems, and is frequently utilized as a drug carrier due to its favorable pharmaceutical and pharmacological characteristics (Dumortier et al., 2006). The aim of this study was to evaluate the influence of poloxamer 407 concentration on the rheological behaviour and printability of probiotic-containing semi-solid formulations.

## Materials and methods

*Materials*

Poloxamer P407 (BASF, Germany) and a commercially available probiotic supplement (Diastop Probio, Alkaloid AD Skopje, North Macedonia) were used for the preparation of the hydrogel formulations.

*Methods*

Four formulations containing 6% probiotic, as well as differing concentrations of P407 were investigated: F1 (25%), F2 (30%), F3 (35%), and F4 (40%). The P407 gels were made using the cold method, and refrigerated overnight at 4°C. After that the probiotic was incorporated into the hydrogel base and mixed until a homogeneous dispersion was achieved.

Rheological characterization was performed using an amplitude sweep test, described by Dutta et al. (2021), and modified for the purposes of this study. The test was conducted at 25°C and 1Hz (MCR 92, Anton Paar, Austria), across 31 strain points within 500 seconds, where shear stress, storage modulus, loss modulus, loss factor, complex viscosity, and torque were measured.

Printability was evaluated using established extrusion bioprinting protocols that assess rheological behavior and printing performance to predict shape fidelity during and after deposition (O'Connell et al., 2020). The evaluation included filament formation after extrusion through a 0.41 mm nozzle, layer-stacking ability determined by

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manual cross-deposition, and tablet printing using a BioX 3D bioprinter (Cellink, Sweden).

## Results and discussion

Rheological measurements demonstrated a concentration-dependent increase in viscoelastic strength with increasing P407 content. The storage modulus (G′) and loss modulus (G″) data showed that all four formulations exhibited a pronounced viscoelastic plateau within the linear viscoelastic region (LVR). F1 displayed the narrowest plateau range (0.125–1.260% strain), whereas F4 maintained the plateau over the widest range (0.125–3.160% strain), indicating greater structural stability and resistance to deformation at higher P407 concentrations.

These findings were further supported by the loss factor results, which showed that the shear strain required for the onset of structural breakdown and flow behaviour increased with polymer concentration. The transition occurred at 5.48% strain for F1 and at 12.70% strain for F4.

The complex viscosity of the formulations ranged from approximately $2.21 \times 10^6$ to $3.05 \times 10^6$ mPa·s, with F4 exhibiting the highest value, consistent with a stronger gel network and greater resistance to deformation.

A similar trend was observed in the shear stress–shear strain relationship. F1 reached the flow region at the lowest shear strain (2.54%), whereas F4 required the highest shear strain (6.23%), further confirming the enhanced structural integrity associated with increasing P407 concentration.

F1 produced filaments with pronounced curvature and poor strand uniformity following extrusion, whereas the filaments generated by F4 were straighter and more continuous. The progressive reduction in filament curvature observed from F1 to F4 indicates that increasing P407 concentration improves filament stability and shape retention after extrusion, both of which are important indicators of printability and shape fidelity.

The layer-stacking test further highlighted differences in post-extrusion behaviour. F1 produced partially merged layers with limited structural definition, while F2, F3 and F4 exhibited distinct layer boundaries and maintained the intended architecture after deposition. These findings suggest that higher P407 concentrations promote faster structural recovery following extrusion, enabling the deposited material to better support subsequent layers and preserve the designed geometry (O'Connell et al., 2020).

Consistent with these observations, tablets printed using F1 showed poor layer definition and reduced structural fidelity. In contrast, tablets prepared from F2, F3 and F4 exhibited well-defined layers, regular geometry and good overall shape fidelity. The improved printing performance of these formulations is in agreement with the rheological data, which demonstrated increased viscoelastic strength and greater resistance to deformation with increasing P407 concentration.

## Conclusion

Increasing the concentration of poloxamer 407 improved rheological properties and printability of the probiotic formulations, highlighting the importance of polymer concentration for stable extrusion and structural fidelity in semi-solid extrusion three-dimensional printing.

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