Assessing rheological properties of oxidized *Moringa oleifera* gum and carboxymethyl chitosan-based self-healing hydrogel for additive manufacturing applications

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**Abstract**
Rheology plays a vital role in pneumatic three-dimensional (3D) printing of hydrogels. This study investigates the rheological behavior of a novel self-healing hydrogel (O-MOG/CMCh) formed by a Schiff base crosslinking reaction between oxidized *Moringa oleifera* gum (O-MOG), a biodegradable antimicrobial polysaccharide, and carboxymethyl chitosan (CMCh), a water-soluble biocompatible chitosan derivative. Three hydrogel formulations were designed using 5% w/v of CMCh with varied concentrations of O-MOG (3% w/v, 4% w/v, and 5% w/v) and evaluated through rheology analyses, including frequency sweeps, amplitude sweeps, oscillatory thixotropy, and gelation kinetics. These tests revealed that the material has shear thinning, self-healing properties, a high linear viscoelastic region (LVE), and gel formation times ($t_{gel}$) of 3.23–4.57 min. The hydrogel synthesized with 5% w/v of O-MOG composition exhibited the best characteristics for printability based on rheological assessments, and this composition was used for further printing assessment, where bi-layered 4 × 4 and 2 × 2 grids were successfully printed using 22 G (0.41 mm) and 23 G (0.34 mm) syringes. All the constructs had a printability index value of 1 ± 0.13 and spreading ratios <6.5, demonstrating the feasibility of employing the synthesized hydrogel as an acellular matrix via additive manufacturing.

**Highlights**
- Self-healing hydrogel was prepared by mixing the precursors through a cannula.
- Rheology was examined using standard tests for printability assessment.
- 3D printability was achieved using two different gauze syringes.
- Printability parameters were recorded and analyzed for the constructs.

**KEYWORDS**
3D printability, additive manufacturing, carboxymethyl chitosan, *Moringa oleifera* gum, rheology, Schiff base
1 | INTRODUCTION

3D printing forms three-dimensional objects by successive adding layers of material as per the programmed model. Polymeric hydrogels are generally printed using the extrusion 3D printing method. Investigating the rheological properties of hydrogel used in 3D printing is essential for understanding their deformation and flow characteristics during printing. This analysis is critical for achieving desired object properties and ensuring successful printing outcomes. Rheology offers valuable insights into how materials are made, whether in liquid or solid form, aiding manufacturers and researchers in optimizing printing processes, anticipating material responses, and maintaining the quality and effectiveness of 3D-printed items. This information allows us to predict whether the material can be successfully extruded through a print nozzle, how well it will hold its shape after deposition, the potential for print defects due to factors like sagging or over-extrusion, and how printing parameters might need to be adjusted to optimize results. Different rheological tests include shear-thinning behavior, amplitude sweep test, step-strain analysis, frequency sweep test, yield stress analysis, and time sweep experiments are described, and the results of those tests are reported before the 3D printing of polymeric materials.

Polysaccharides, natural polymers that are abundant, versatile, biocompatible, and relatively inexpensive, gained a new choice of material for 3D printing applications, especially in drug delivery, tissue engineering, and other fields. Common polysaccharides used in 3D printing include chitosan, alginate, gelatin, and cellulose, which possess favorable biomimetic properties. Furthermore, Moringa oleifera gum, a naturally occurring polysaccharide, is extracted from the Moringa tree. It has several medicinal properties, including anti-inflammatory properties that reduce fever; antioxidant properties that guard against oxidative stress; anti-asthmatic properties that reduce fever; antioxidant properties that guard against oxidative stress; anti-asthmatic properties that constrict and bind tissue; and rubefacient properties that, when applied, cause the skin to become red to promote blood circulation. Chitosan, a naturally occurring polycationic linear polysaccharide, originates from chitin, the primary structural component found in the exoskeletons of insects and crustaceans (such as shrimps and crabs), as well as in the cell walls of fungi. It is the second most plentiful natural polysaccharide after cellulose. Carboxymethyl chitosan, produced by the deacetylation of chitosan, possesses hydrophilic characteristics and has been used in 3D bioprinting applications. It has non-toxic, biocompatible, and biodegradable properties, which make it useful in biomedical utilization.

The 3D construct is formed using different mixture ratios of alginites and carboxymethyl chitosan in a calcium chloride crosslinker solution. Bider et al. synthesized a hydrogel using alginate dialdehyde and gelatin in the presence of calcium chloride and microbial transglutaminase, having 3D printability used for bone tissue engineering. Another group of researchers also synthesized a 3D printable hydrogel using alginate dialdehyde and gelatin scaffolds incorporating polydopamine with silicon dioxide and copper oxide nanoparticles for bone regeneration. Ettoumi et al. fabricated a nanocomposite polysaccharides hydrogel using fucoidan and chitosan with better 3D printing ability to release polyphenols. Kim et al. designed a 3D printable hydrogel using oxidized and hydrazide-modified hyaluronic acids for potential use as bio-inks. A biocompatible and 3D printable hydrogel was synthesized using double-quaternized chitosan with cystamine-based non-isocyanate polyurethane, tailored for biomedical applications. A 3D printable hydrogel derived from carboxymethyl chitosan and oxidized hyaluronic acid via Schiff base reaction utilized for biomedical applications. A 3D printable bio-ink was derived from chitosan and gallic acid for tissue engineering applications. Wang et al. designed a 3D printable hydrogel in the form of the heart valve using arginine-modified polylysine and oxidized hyaluronic acid through dynamic acyl-hydrazone bonds.

After evaluating the literature based on 3D printing, the novelty of this research includes (1) Unique biomaterial combination material combination. This specific combination has likely not been extensively studied before, especially in additive manufacturing. (2) Focus on self-healing properties: a crucial feature for advanced materials in 3D printing and other additive manufacturing processes. (3) Application in additive manufacturing: By assessing the rheological properties of this hydrogel for additive manufacturing applications, the study bridges the gap between novel biomaterials and advanced manufacturing techniques. (4) Rheological property assessment: The comprehensive analysis of rheological properties provides valuable insights into the material’s behavior during the additive manufacturing process, which is critical for optimizing printing parameters and final product quality.

This research article is an enhancement in terms of application of our previously published study, which involves the synthesis of an injectable hydrogel using multialdehyde Moringa oleifera gum and carboxymethyl chitosan via Schiff base crosslinking mechanism used in drug delivery. Based on that, the optimized concentration of both the solutions (oxidized Moringa oleifera gum and carboxymethyl chitosan) with some addition was selected for the current study. It is hypothesized that a
hydrogel derived from the combination of oxidized *Moringa oleifera* gum and carboxymethyl chitosan through Schiff base crosslinks may possess adequate rheological properties to be utilized as an ink to fabricate 3D constructs by extrusion-based printing.

This work describes a rheological analysis and extrusion-based 3D bioprinting application of a Schiff-based hydrogel synthesized by combining derivatized chitosan and oxidized *Moringa oleifera* gum. Furthermore, this research may open new avenues for developing advanced, sustainable, and self-healing materials in additive manufacturing, with applications ranging from biomedical devices to industrial components.

## 2 | MATERIALS AND METHODS

### 2.1 | Materials

*Moringa oleifera* gum was obtained from Nutramine Life Science, New Delhi, India (Product code 232154). Chitosan (deacetylation degree of 85%) was bought from Otto Chemical Pvt. Ltd. (C 1906). Sodium hydroxide (030167), sodium periodate (645645) (NaIO₄), and hydroxylamine hydrochloride (565325) were obtained from CDH chemicals. Ethylene glycol (71883), isopropyl alcohol (67-63-0), and monochloroacetic acid (79-11-8) were purchased from Thomas Baker Chemicals Pvt. Ltd. Ethanol (57101) was procured from SRL Chemicals, India. The hydrogels used in this study were synthesized in the laboratory. The oxidation % of O-MOG and the degree of substitution of CMCh were determined to be 87.8% and 67%, respectively. Furthermore, a known amount of O-MOG (3%, 4%, and 5% w/v) was dissolved in distilled water at 600 RPM for 24 h (solution 1). Similarly, CMCh (5% w/v) was dissolved in phosphate buffer saline at pH 7.4 at 800 RPM (solution 2). Then, both solutions were filled into separate syringes (10 mL) and extruded simultaneously into a test tube (20 mL) through a two-way cannula at 37°C (Table 1).

### 2.2 | Methods

#### 2.2.1 | Rheological analysis

Rheological measurements were performed using the Anton Paar MCR 302 rheometer throughout, using 40 mm parallel-plate geometry. The temperature was set at 37°C for all tests. The sample’s viscosity is measured across a range of shear rates, from low to high, to evaluate the viscosity variation. The shear rate sweep was carried out with the shear rate ranging from 0.1 to 100 s⁻¹. The amplitude sweep test was performed to check the linear viscoelastic region at a constant angular frequency of 10 rad s⁻¹, with the strain amplitude ranging from 0.01 to 100%. A frequency sweep test was conducted under a constant strain amplitude of 0.1% to evaluate the synthesized hydrogel properties over frequencies ranging from 0.1 to 100 rad s⁻¹. Loss factor (tan δ) was determined at a constant strain of 0.1% frequency ranges from 0.1 to 100 rad s⁻¹. Oscillatory step strain analysis was conducted under a low (0.01%) and high strain (100%) for three cycles over 10 min. The time sweep test was conducted at 0.1% strain and 1 Hz frequency over 60 min. Yield stress and flow point were also measured under a constant angular frequency of 10 rad s⁻¹, with the strain amplitude ranging from 0.01% to 100%.

#### 2.2.2 | Printing

The printability tests were done using a direct write assembly (Fiber Align, Aerotech Inc., USA). Two bilayered 16 mm × 16 mm designs were made in Robo-CAD software with 4 and 8 mm inter-filament spacing, respectively. The printing speed was kept at 1 mm/s, and the extrusion pressure was 5 ± 1.5 psi for all samples. The sizes of nozzles used were 22 G (0.41 mm), and 23 G (0.34 mm). Printability characteristics were evaluated by calculating the printability index, spreading ratio, and line width. All images were analyzed using the ImageJ software for all measurements.

The perimeter and area of the pores were calculated to determine and assess the printability of the O-MOG/CMCh hydrogels using the printability index (Pr). The Pr value evaluates how well an ink retains its shape after deposition by measuring the degree to which square pores in a grid tend to become rounded. It measures the printing resolution. The printability index was calculated using Equation (1):

\[
Pr = \pi \frac{1}{4} \frac{L^2}{16A}
\]

where \(C\) is the circularity of the enclosed pore, \(L\) stands for the perimeter, and “\(A\)” stands for the pore area.

| TABLE 1 | Concentration of precursors used for hydrogel synthesis. |
|-----------------|-----------------|-----------------|
| **Concentration of O-MOG** | **Concentration of CMCh** | **Hydrogel** |
| 3% (w/v) | 5% (w/v) | O-MOG/CMCh-3 |
| 4% (w/v) | 5% (w/v) | O-MOG/CMCh-4 |
| 5% (w/v) | 5% (w/v) | O-MOG/CMCh-5 |
Spreading ratio (SR) is another parameter used to evaluate the inks’ ability to print precise structures while reducing coalescence and pore closure. SR is calculated as the ratio of the width of the printed filament to the diameter of the nozzle (Equation (2)):

$$SR = \frac{\text{width of extruded strand}}{\text{diameter of the nozzle}} = \frac{t_{\text{filament}}}{d_{\text{nozzle}}} \quad (2)$$

The line widths of the printed filaments were measured by taking multiple measurements of the width of the printed lines in each construct. The measurements' averages were taken and plotted on a bar graph. Line width accuracy ensures consistent material deposition for desired part design and functionality. Ideally, the line width should be the same as the inner diameter of the nozzle.

3 | RESULTS AND DISCUSSION

This study assesses the feasibility of 3D printing for fabricated hydrogels composed of O-MOG and CMCh via the Schiff base reaction mechanism. Understanding the printable nature of synthesized hydrogels necessitates an examination of their rheological properties. Therefore, rheological investigations were conducted to elucidate the flow characteristics and viscoelastic attributes of all three hydrogel samples in which the concentration of O-MOG varies from 3% w/v to 5% w/v and CMCh concentration remains constant (5% w/v).

Figure 1 illustrates the flow behavior of O-MOG/CMCh hydrogels across a spectrum of shear rates ranging from 0.1 to 100 s⁻¹. All samples exhibit shear-thinning behavior, a decreasing viscosity (O-MOG/CMCh-1 = 1,293,800 mPa.s to 500 mPa.s; O-MOG/CMCh-4 = 359,020 mPa.s to 380 mPa.s; O-MOG/CMCh-5 = 2,208,800 mPa.s to 766 mPa.s) was observed with increasing shear rate. This significant reduction in viscosity is beneficial for 3D printing, enabling smooth hydrogel flow through the fine printing nozzles. Throughout the test, hydrogels with the highest amount of oxidized MOG (O-MOG/CMCh-5) exhibited the highest viscosity. In comparison, the hydrogel formulated with the lowest concentration of oxidized MOG (O-MOG/CMCh-3) demonstrated the lowest viscosity among all the samples. With a higher O-MOG concentration, more aldehyde groups become available for the Schiff base reaction. This increases Schiff base linkages, increasing the hydrogel’s viscosity. These results show that the material has shear-thinning properties and can be extruded from the nozzle. Shear-thinning properties enable efficient material extrusion through fine nozzles, a crucial factor for pneumatic and extrusion-based printing techniques. The hydrogels formed by a single Schiff base linkage in Ding et al.’s work also show a drop of about three orders of magnitude over the same shear rate range (15,000 Pa.s to ~0 Pa.s). Hu et al.’s work on a thermoresponsive hydrogel also shows similar outcomes and is suited for printing (100,000 Pa.s to ~0).

Dynamic strain sweeps were performed to identify the LVE region, where storage modulus ($G’$) and loss modulus ($G''$) remain stable. The LVE region represents the range of applied strain where the hydrogel exhibits linear viscoelastic behavior. Within this region, $G’$ and $G''$ remain constant, with $G''$ being lower than $G’$ throughout. This indicates minimal energy loss and an ideal elastic response. This analysis provides insights into the extent of deformation a material can endure before its internal structure deteriorates. The test identifies the LVE region where the material can be extruded without compromising its structural integrity. Amplitude sweeps conducted from 0.01% to 100% strain revealed that the hydrogels possess a large LVE region, indicating their ability to withstand a wide range of strains while maintaining linearity, as depicted in Figure 2. As the hydrogel O-MOG/CMCh-5 forms the highest number of Schiff linkages, it exhibits more solid-like behavior and consequently has the highest $G’$ value in the LVE region. Earlier studies on dynamic glycol chitosan hydrogels formed through Schiff base linkages have demonstrated comparable results in amplitude sweep experiments. The decrease in storage modulus and increase in loss modulus specifies the disruption of the inner structure of hydrogel. Therefore, the LVE region strain value (0.1%) was selected for the dynamic frequency sweep test. Yu et al. fabricated a hydrogel derived from carboxymethyl chitosan and oxidized hyaluronic acid crosslinked through the Schiff base reaction; amplitude study shows that hydrogel contains a
minimum concentration of oxidized polysaccharide shows favorable mechanical strength.24

By varying the applied frequency, a frequency sweep shows how easily a gel deforms under different printing speeds, impacting 3D printability. Figure 3 shows the dynamic frequency sweep analysis, and it is observed that for all concentrations, the \( G' \) consistently exceeded the \( G'' \) across the frequency range of 0.1 to 100 rad s\(^{-1}\). Again, this indicates a predominantly elastic behavior rather than a fluid-like state in all gels. The hydrogel with the highest concentration of oxidized MOG (O-MOG/CMCh-5) also has the highest \( G' \) due to a more significant number of Schiff base linkages. Moreover, \( G' \) consistently exhibited a value five times greater than \( G'' \) for all hydrogel concentrations, emphasizing their predominantly elastic nature. The \( G' \) and \( G'' \) values showed minimal variation across the frequency range of 0.1–100 rad s\(^{-1}\), indicating consistent viscoelastic behavior at different frequencies. Wang et al. observed analogous findings in their study on 3D printing of a self-healing polysaccharide hydrogel, where the storage modulus exhibited frequency-independent behavior.30,32

In the LVE region, at 0.1% strain, the behavior of a material is characterized by its tan delta (\( \tan \delta \)) values. This ratio, calculated as the \( G'' \) divided by the \( G' \), reflects the balance between energy dissipation (viscosity) and energy storage (elasticity). When \( \tan \delta \) exceeds 1, the material behaves predominantly as a viscous liquid. Conversely, \( \tan \delta \) below 1 values signify that the material exhibits predominantly elastic, solid-like behavior.2 A loss factor of less than one indicates that the material is more elastic than viscous, which is desirable for maintaining structural integrity during printing and preventing excessive flow or spreading after deposition. Figure 4 shows that \( \tan \delta \) consistently remains below 1 across the tested frequency range for all hydrogels, indicating that elastic effects rather than viscous effects mainly govern stresses. Cheng et al. highlighted that the value \( \tan \delta \) ranging from 0.2 to 0.7 is ideal for printing material.33

Our investigation revealed that among the studied samples, the O-MOG 5% gel was the sole composition exhibiting a loss factor surpassing 0.2, rendering it the most suitable candidate for printing applications.

The material needs to recover its viscosity almost instantly after extrusion. This rapid ‘rebuilding’ allows the extruded filament to hold its shape, preventing collapse or unwanted spreading before it solidifies. Thus, the oscillatory step strain test shows the self-healing
property of the material. Evaluation of thixotropic properties includes testing at high and low strain amplitudes. The material’s ability to rapidly crossover, demonstrating reversible liquid–solid transitions, is crucial for printed filament shape retention. Figure 5 shows the oscillatory strain experiment, in which all the hydrogels were subjected to low (0.01%) and high (100%) strain values, giving them enough time to undergo gel-to-sol and sol-to-gel transitions. The self-recovery process was repeated for three cycles, and it was observed that under a low strain of 0.01%, all O-MOG/CMCh hydrogels quickly regained its mechanical strength. $G'$ of all three hydrogels exhibited almost complete recovery within 20 s, highlighting the rapid and full instantaneous recovery of viscoelastic properties and the self-healing capability. Maity et al. found similar results with a chitosan-based hydrogel for strains up to 100% and showed self-healing properties. Hu et al. also performed a similar study of 100% strain for a biomaterial ink and found complete recovery necessary for 3D printability. This ensures that extruded filaments experience minimal to no deformation or distortion upon deposition on the printing platform, demonstrating the material’s suitability for maintaining structural integrity throughout the printing process.\(^{35}\)

Figure 6 shows the time sweep assessment for all hydrogels. The gelation time ($t_{gel}$) was determined by the crossover point, where the $G'$ exceeded the $G''$, marking the onset of gelation. This transition indicated the initiation of crosslinking facilitated by forming Schiff base linkages. The rate of increase in $G'$ outpaced that of $G''$, signaling a pronounced shift toward a more solid-like state in the viscoelastic behavior of the system.\(^{36}\) Across the investigated formulations, gelation time ranged from 3.23 ± 0.05 to 4.59 ± 0.05 min, with the O-MOG/CMCh-3 hydrogel having the highest gelation time and O-MOG/CMCh-5 possessing the least. This is in line with theory as O-MOG/CMCh-5 gel has the highest number of Schiff linkages out of all variants due to a more significant number of aldehyde groups present so that it can undergo gelation at an increased rate. Puertas-Bartolomé et al. found similar gelation times in their study on 3D printing of a reactive hydrogel system formed by Schiff base reaction of carboxymethyl chitosan with oxidized hyaluronic acid.\(^{37}\)

This test is an extension of the amplitude sweep test, and it measures the $G'$ and $G''$ against shear stress to identify the yield and flow points. The yield point, where $G'$ drops significantly, indicates the transition from solid-like to liquid-like behavior and flow. The crossover point, where
$G''$ surpasses $G'$, represents the further transition into liquid-like behavior, approximating the flow point. A well-defined yield point is crucial for shape retention after extrusion, as values that are too low or too high can lead to structural defects or excessive extrusion forces, respectively. The amplitude sweep test obtained all hydrogels' yield stress and flow point values. Figure 7 shows that increasing the O-MOG concentration (3% w/v to 5% w/v) also increased yield stress values from 88 to 232 Pa. This suggests that the hydrogels become more rigid as the O-MOG concentration increases. The flow point values of hydrogels O-MOG/CMCh-3, O-MOG/CMCh-4, and O-MOG/CMCh-5 are 320, 331, and 340 Pa, respectively, suggesting an increasing resistance to flow or deformation. Haider et al. conducted a similar test on a thermosensitive hydrogel, and their reported findings align closely with the present study.38

### 3.1 3D printing of hydrogels

After analysis of all the rheological parameters, it was demonstrated that the hydrogel O-MOG/CMCh-5 found the best rheological properties in most tests. Therefore, the hydrogel O-MOG/CMCh-5 was chosen for printability...
Two grid patterns, 4 × 4 and 2 × 2, with two layers of extruded hydrogel stacked vertically and inter-filament distances of 8 and 4 mm, respectively, were printed using nozzles with inner diameters of 0.34 mm (23 G) and 0.41 mm (22 G), resulting in a total of four constructs (Figure 8A). In the case of the 24 G nozzle, the printer could not provide the required higher pressure for extrusion. The Pr, SR, and line width were calculated for all four constructs.

Figure 8C shows the application of the printability formula for different pore shapes in which a Pr value of 1 signifies perfectly square holes. In contrast, Pr values less than 1 suggest more circular holes and merged filaments, and Pr values greater than 1 indicate irregular shapes and bumpy extrusion. Larger Pr values correlate with greater gelation and vice versa. The mean Pr values were 0.9187878, 1.0136814, 0.8768435, and 0.9387235 for the four constructs A (23 G), A (22 G), B (23 G), and B (22 G), respectively (Figure 9). These results correspond to another work on a self-cross linkable chitosan-based hydrogel made using Schiff base linkages. The constructs fabricated using the 22 G (0.41 mm) nozzle demonstrated superior Pr values, indicating that for this particular composition of O-MOG (5% w/v) and CMCh (5% w/v), 22 G represents the minimum feasible nozzle diameter.

Lower spreading ratios are preferred to produce hydrogel structures with enhanced precision. The smallest spreading ratio among the provided samples was identified for construct B, printed using a 0.41 mm (22 G) inner diameter nozzle, measuring approximately 4.9. All spreading ratios recorded are below 6.5 (Figure 10). The constructs printed using nozzles with a 0.41 mm (22 G) inner diameter also showed the lowest SR values among all four grids. This observation further reinforces that 22 G nozzles are well-suited for printing for the given composition of gels. Ideally, a spreading ratio close to 1 is desired. But Ioannidis et al.’s work on an alginate-gelatin mixture as bio-ink, spreading ratios higher than 10 have also been reported.

The line width for all printed samples was determined. Figure 11 shows construct A, printed with a 0.34 mm (23 G) inner diameter nozzle, exhibited the widest line width among all samples, measuring approximately 2.23 mm. This finding corresponds with the spreading ratio of construct A (23 G), which is the highest among all sample constructs. Interestingly, this width surpassed that of constructs printed with a 0.41 mm (22 G) inner diameter nozzle. This again suggests that employing nozzles with inner diameters smaller than 22 G compromises the structural integrity of the extruded material, leading to unsatisfactory outcomes. Once again, citing the work by Ioannidis et al., line widths close to 3 mm from 25 G diameter nozzles have been reported.
4 | CONCLUSION

The most common rheological assessments were carried out for three O-MOG/CMCh hydrogels containing varied concentrations of O-MOG (3% w/v to 5% w/v) with constant CMCh concentration (5% w/v) formed by Schiff base reaction. Time sweep test showed that hydrogel containing 5% w/v of O-MOG, undergoing solvent transition at 3.23 ± 0.05 min, and amplitude sweep test demonstrated a relatively high mechanical strength of $G' \approx 2.4$ kPa. Thus, O-MOG/CMCh-5 exhibited the best properties for printing purposes. At the same time, all O-MOG/CMCh hydrogels are highly shear thinning with good structure recovery properties. Oscillatory thixotropy results show that the material has excellent self-healing capabilities. The rheological properties suggest that the O-MOG/CMCh hydrogels, formed by Schiff base linkage, are fit for 3D printing applications. The O-MOG/CMCh-5 hydrogel was then employed to successfully print 4 x 4 and 2 x 2 grids using 0.41 mm (22 G) and 0.34 mm (23 G) inner diameter nozzles. On visual analyses of the constructs, it is observed that the extruded filament is more uniform when the gel is extruded from the 22 G nozzle. The uniformity begins to deteriorate as the nozzle size decreases to 23 G. The printability index of all constructs is within the acceptable range, with the constructs printed using a 0.41 mm (22 G) inner diameter nozzle showing the best results as their Pr values are closest to one. The lower Pr value is ≈0.87 for construct B, printed using a 23 G nozzle. Spreading ratio and line width data also show better results for grids printed using 22 G nozzles. This suggests that the material cannot recover completely after it is extruded through the 0.34 mm (23 G) inner diameter nozzle. A possible reason for this is that extruding the gel through nozzles with diameters smaller than the 22 G nozzle disrupts the internal structure of the gel to a degree where it begins to clog the nozzle. Hence, a 22 G inner diameter nozzle is best suited for this composition. Further material optimization is needed to use nozzles of lower diameters and get better results for Pr and SR values. Different compositions, different preparation methods, or the addition of crosslinkers may lead to better shape fidelity, mechanical properties, and uniform extrudability with lower-diameter nozzles.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data will be made available on request.

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