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# An Open-Source Continuous Fiber Extruder for Long-Fiber Reinforced Hydrogel Bioprinting

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**Abstract**
Hydrogels are widely explored in biomedical engineering, soft robotics, and biofabrication due to their high water content, flexibility, and biocompatibility. However, their limited mechanical strength often restricts their use in applications requiring structural stability or load resistance. In this work, a compact and cost-effective Continuous Fiber Extruder (CFE) is developed and integrated with a standard desktop 3D printer to enable the embedding of long, continuous fibers within hydrogel constructs during printing. The system is designed using open-source hardware and employs compliant silicone rollers driven by a microstepped stepper motor to ensure smooth and damage-free feeding of delicate fibers. The CFE operates alongside a syringe-based hydrogel extruder and is compatible with the Freeform Reversible Embedding of Suspended Hydrogels (FRESH) printing approach. Experimental calibration confirms accurate control of fiber feed length, achieving positional accuracy greater than 98% across multiple embedding patterns. Mechanical testing of reinforced hydrogel specimens demonstrates significant enhancement in tensile performance, with strength and stiffness improvements observed depending on the fiber material and layout. The proposed extruder provides an accessible and reproducible platform for fabricating mechanically reinforced hydrogel composites using low-cost desktop equipment. This approach lowers the barrier to long-fiber embedded hydrogel printing and supports further research in bioinspired structures, soft functional materials, and biomedical applications.

**Keywords:** Hydrogels; Continuous Fiber Extruder (CFE); FRESH; 3D bioprinting; Reinforcement; Replistruder

## 1. Introduction

Hydrogels are three-dimensional polymer networks capable of retaining large amounts of water, making them attractive for applications such as tissue engineering, biomedical devices, soft robotics, and controlled drug delivery due to their biocompatibility and tunable properties [1]. The combination of hydrogels with additive manufacturing has enabled the fabrication of complex geometries with spatially controlled architectures, which are difficult to achieve using conventional molding or casting techniques [2]. Among the various additive manufacturing methods, extrusion-based hydrogel printing has gained widespread acceptance because it is compatible with soft, shear-sensitive materials and can be implemented using low-cost, open-source desktop platforms [3].

Despite these advantages, the mechanical weakness of most hydrogels remains a major limitation. Printed hydrogel structures typically exhibit low tensile strength and stiffness, which restricts their use in load-bearing or mechanically demanding environments [4]. To address this issue, several reinforcement strategies have been investigated, including the incorporation of nanoparticles, short fibers, and nanofillers into hydrogel matrices [5]. While such approaches can improve specific mechanical or functional properties, they generally provide limited control over reinforcement orientation and spatial distribution, leading to inefficient stress transfer and isotropic mechanical behavior [6].

The Freeform Reversible Embedding of Suspended Hydrogels (FRESH) technique represented a significant advancement in hydrogel 3D printing by enabling the fabrication of soft and low-viscosity bioinks within a temporary support bath [7]. This approach allows complex and high-fidelity structures to be printed without collapse during fabrication. However, FRESH-printed hydrogels still suffer from limited mechanical robustness once removed from the support medium, highlighting the need for additional reinforcement strategies [8]. Recent studies have demonstrated that embedding continuous, long fibers within hydrogels during printing can substantially enhance mechanical performance while maintaining flexibility and compliance [9]. Long-fiber reinforcement offers distinct advantages over short-fiber or particulate reinforcement by enabling programmable fiber paths and anisotropic mechanical behavior tailored to specific loading conditions [10]. Continuous fiber embedding has been shown to significantly improve tensile strength, stiffness, and durability of hydrogel constructs, particularly when fiber orientation is aligned with the principal load direction [11]. However, existing implementations of long-fiber embedded hydrogel printing typically rely on specialized research setups or proprietary systems, limiting their accessibility and reproducibility [12]. Commercial continuous fiber printers are primarily designed for thermoplastic materials and are unsuitable for soft, water-based hydrogel systems [13].

Recent efforts toward open-source bioprinting hardware have demonstrated the feasibility of developing low-cost extrusion systems with improved control and monitoring capabilities [14]. Nevertheless, a practical and modular solution for continuous fiber embedding in hydrogels that is compatible with widely available desktop 3D printers remains limited [15]. Moreover, challenges related to gentle handling of fragile fibers, precise feed control, and synchronization with hydrogel extrusion have yet to be fully addressed in low-cost platforms [16].

In this work, a compact and cost-effective Continuous Fiber Extruder (CFE) is developed for long-fiber embedded hydrogel 3D printing using a standard desktop 3D printer. The proposed system employs compliant silicone rollers driven by a microstepped stepper motor to enable smooth and damage-free feeding of biological and synthetic fibers [17]. The extruder is integrated with a syringe-based hydrogel extrusion system and operated in conjunction with the FRESH printing method to achieve accurate fiber placement within printed hydrogel structures [18]. The performance of the system is evaluated through calibration experiments, fiber embedding accuracy measurements, and mechanical testing of reinforced hydrogel specimens. This study demonstrates that precise long-fiber reinforcement of hydrogels can be achieved using low-cost, open-source hardware, supporting broader adoption of reinforced hydrogel printing for bioinspired structures, soft functional materials, and emerging biomedical applications [19].

## 2. Methodology

The experimental setup employed in this study is based on a standard desktop 3D printer integrated with a syringe-based hydrogel extrusion system and a custom-designed Continuous Fiber Extruder (CFE). The printer motion system provides accurate Cartesian positioning, while the hydrogel ink is deposited into a gelatin-based support bath using the Freeform Reversible Embedding of Suspended Hydrogels (FRESH) technique, which enables stable fabrication of soft hydrogel structures during printing [1]. The CFE is mounted adjacent to the hydrogel extruder on the printer carriage, allowing synchronized motion and simultaneous deposition of hydrogel and continuous fibers. A schematic representation of the integrated printing system and component arrangement is shown in Fig. 1.

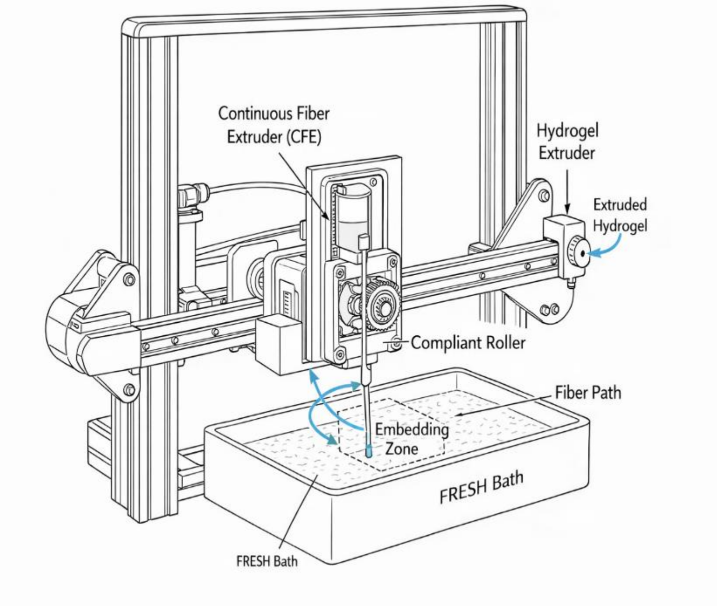


Fig.1 A schematic representation of the integrated printing system

The CFE operates on a dual-roller pinch mechanism designed to ensure smooth and damage-free feeding of fragile fibers. The system consists of a driven roller coupled to a stepper motor and a freely rotating roller supported by a bearing. Both rollers are coated with compliant silicone to enhance frictional grip while preventing fiber crushing or slippage, which is critical for biological fibers such as collagen and silk [2]. The fiber is guided through low-friction channels and aligned directly beneath the hydrogel nozzle so that it becomes embedded within the extruded hydrogel during deposition. The working principle of the fiber feeding mechanism and its alignment with the hydrogel extrusion path are illustrated in Fig. 2.

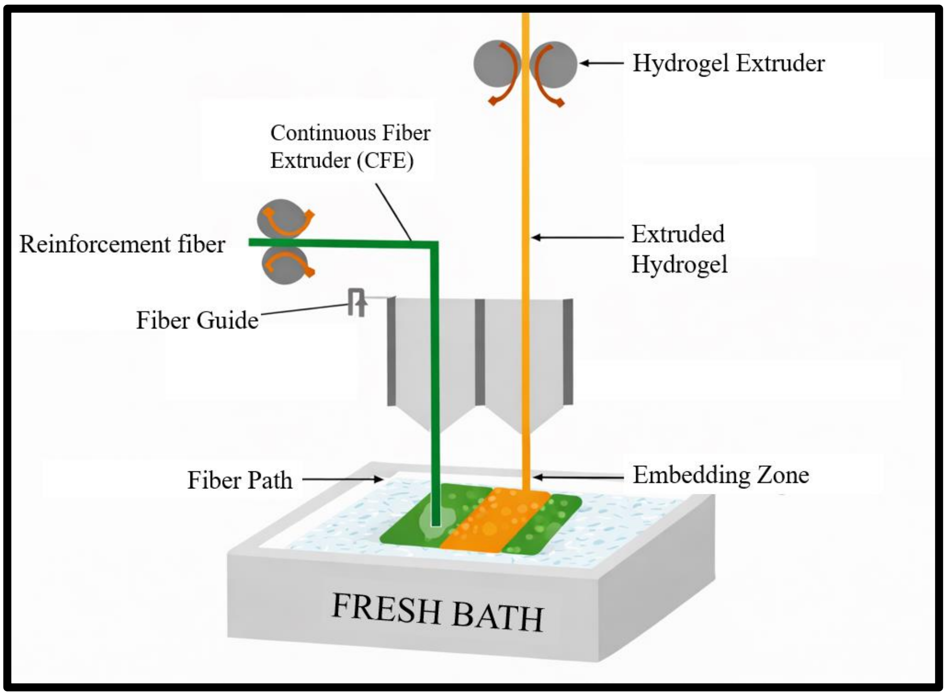


Fig. 2 . Working principle of the fiber feeding mechanism

The CFE is integrated with the desktop printer without modifying the original gantry or motion hardware, preserving the modularity and accessibility of the system. Fiber extrusion is controlled using an auxiliary extruder channel of the printer controller, enabling precise regulation of fiber feed length through standard G-code commands. Microstepping control of the stepper motor provides high positional resolution, allowing accurate synchronization between fiber feeding and hydrogel deposition [3]. Calibration is performed by issuing incremental fiber extrusion commands and measuring the corresponding fiber displacement to determine appropriate correction factors for consistent operation.

Hydrogel printing is carried out using a sodium alginate-based ink extruded into a gelatin microparticle slurry prepared for FRESH printing [1]. A range of continuous fibers, including collagen, silk, polyester, and stainless steel microfibers, are evaluated to demonstrate the versatility of the CFE across biological, synthetic, and metallic materials. Printing parameters such as travel speed, fiber feed rate, and fiber spacing are selected to ensure stable embedding without fiber buckling or misalignment. Representative fiber-embedded hydrogel patterns printed for calibration and validation purposes are shown in Fig. 3.

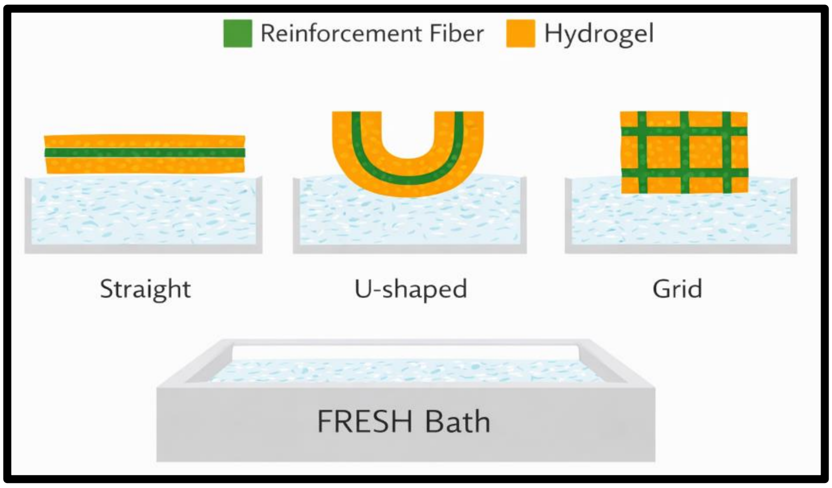


Fig.3 Representative fiber-embedded hydrogel patterns

To evaluate system performance, test patterns including straight lines, curved paths, and grid layouts are printed to assess fiber placement accuracy and repeatability. Following printing, reinforced and non-reinforced hydrogel specimens are carefully removed from the support bath and subjected to uniaxial tensile testing to quantify improvements in mechanical performance resulting from continuous fiber reinforcement [11]. The methodology ensures repeatable fabrication and reliable assessment of the proposed low-cost continuous fiber embedding approach for hydrogel 3D printing.

**Design and Fabrication**

The experimental platform developed in this work is based on a desktop 3D printing system comprising a Creality Ender-3 motion framework, a syringe-based hydrogel extrusion unit, and a custom-designed Continuous Fiber Extruder (CFE) mounted adjacent to the syringe extruder. The syringe pump assembly is adapted from an open-source Replistruder design and is used to deposit hydrogel ink into a gelatin microparticle slurry following the Freeform Reversible Embedding of Suspended Hydrogels (FRESH) approach. During printing, the FRESH support bath provides temporary mechanical support to the hydrogel constructs and is liquefied after printing to enable gentle retrieval of the fabricated samples. The complete fabricated and assembled CFE–syringe pump system mounted on the desktop 3D printer is shown in Fig. 4, highlighting the integrated and modular nature of the setup.

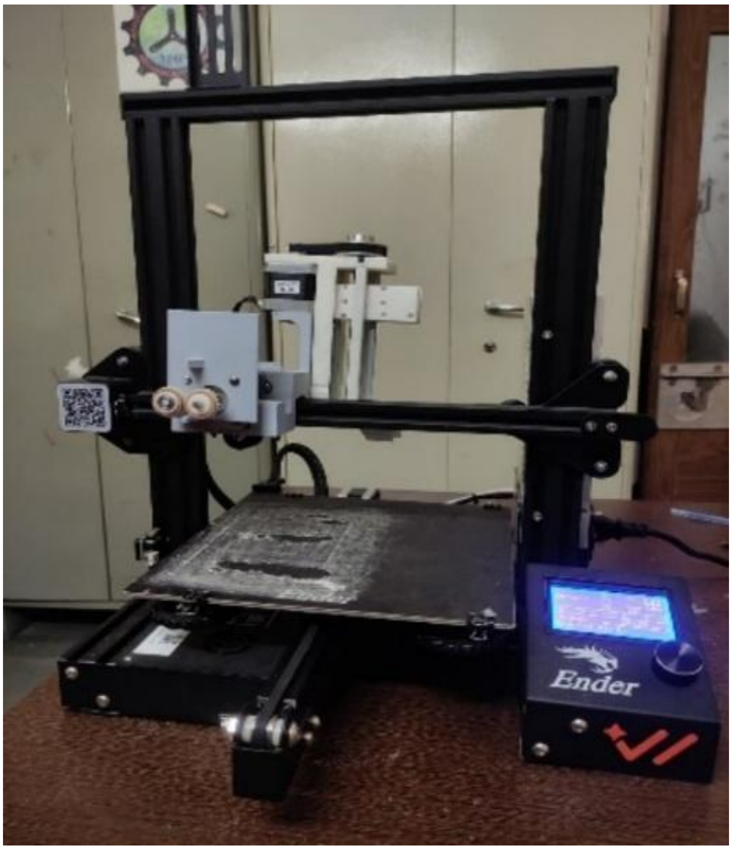


Fig.4 assembled CFE + syringe pump photograph

The CFE is designed to enable precise and damage-free feeding of continuous reinforcement fibers during hydrogel printing. Key design considerations include gentle handling of fragile biological fibers such as collagen and silk, high positional resolution for accurate fiber placement, low overall system cost, and seamless integration with existing printer electronics and firmware. To meet these requirements, a dual-roller pinch mechanism is adopted in which a motor-driven roller and a freely rotating roller apply controlled compressive force on the fiber. Both rollers are coated with compliant silicone to enhance friction while preventing fiber crushing. The rollers are mounted on 3D-printed PLA gears, with the driven roller supported by a miniature bearing to minimize resistance. Fiber alignment is maintained using upper and lower pipette-tip guides, which ensure consistent positioning of the fiber and direct it into the hydrogel deposition region within the FRESH bath.

All mechanical components of the CFE are designed using CAD software and fabricated using fused filament fabrication with PLA material. The printed components form a compact backbone that supports the stepper motor, roller assembly, and fiber guides. Silicone rollers are produced by molding two-part silicone putty in custom dies and bonding the cured silicone wheels to the printed gear faces. A NEMA-17 stepper motor is coupled to the drive gear using a set-screw arrangement, while the driven gear rotates freely on a press-fit bearing. The use of readily available materials and desktop fabrication techniques ensures that the complete CFE can be produced at low cost while maintaining sufficient mechanical robustness for repeated operation.

The CFE and syringe pump assembly are integrated onto the printer carriage without modifying the original gantry or motion system of the desktop printer. The syringe pump is positioned to deposit hydrogel vertically into the FRESH bath, while the CFE is mounted alongside such that the reinforcement fiber is introduced directly beneath the hydrogel extrusion nozzle. This spatial alignment enables simultaneous hydrogel deposition and fiber embedding along programmed toolpaths, as visible in the assembled system shown in Fig. 4. The modular mounting approach allows easy installation, adjustment, or removal of the CFE without affecting the base printer functionality.

Actuation of the CFE is achieved using a stepper motor driven by the printer's existing stepper driver hardware. The motor, having a step angle of 0.9°, is operated under microstepping control to achieve fine resolution in fiber feed length. The CFE is configured as a secondary extruder (E1) in the printer firmware, enabling control through standard G-code extrusion commands. This configuration allows synchronized operation of the syringe-based hydrogel extrusion and fiber feeding without the need for additional control electronics. Calibration factors are implemented through slicer or firmware extrusion multipliers to compensate for minor deviations between commanded and actual fiber feed lengths.

Hydrogel printing experiments are conducted using a 4% w/v sodium alginate bioink, dyed for visual clarity, and a standard gelatin microparticle slurry prepared for FRESH printing. A variety of continuous reinforcement fibers are evaluated, including electrochemically aligned collagen fibers, silk thread, polyester sewing thread, and stainless steel microfilament, to demonstrate the versatility of the developed CFE. Printing parameters such as travel speed, fiber feed rate, fiber spacing, and syringe extrusion flow rate are adjusted to ensure stable embedding of fibers without buckling, misalignment, or drag.

System calibration is performed by issuing incremental fiber extrusion commands and measuring the corresponding fiber displacement to determine an extrusion correction factor. Fiber placement accuracy is evaluated by printing representative test patterns such as straight lines, U-shaped paths, grids, and web structures. Following printing, reinforced and non-reinforced hydrogel specimens are removed from the support bath and subjected to uniaxial tensile testing to assess the effectiveness of continuous fiber reinforcement. The described design and fabrication approach demonstrates that precise long-fiber embedded hydrogel printing can be achieved using a low-cost, open-source, and easily reproducible desktop platform.

## 3. Results and Discussion

The performance of the developed Continuous Fiber Extruder (CFE) was evaluated through calibration of fiber feed, assessment of fiber embedding accuracy, and mechanical characterization of reinforced hydrogel specimens. Fiber feed calibration was carried out by issuing incremental extrusion commands (E5, E10, E15, and E20) and measuring the corresponding physical fiber displacement. The comparison between commanded and measured fiber lengths is summarized in Table 1. After applying the extrusion correction factor, the average error across all commands was maintained below 2%, demonstrating reliable and repeatable fiber feed control. The near-linear relationship between commanded extrusion length and measured fiber displacement confirms the effectiveness of microstepped roller-based feeding, as illustrated in Fig. 5, where the measured values closely follow the ideal linear trend.

Table 1. Calibration results for fiber feed length

| Step Command | Expected Length (mm) | Measured Length (mm) | Error (%) |
|---|---|---|---|
| E5 | 19.25 | 19.0 | 1.30 |
| E10 | 38.50 | 38.1 | 1.00 |
| E15 | 57.75 | 56.9 | 1.47 |
| E20 | 77.00 | 75.8 | 1.55 |

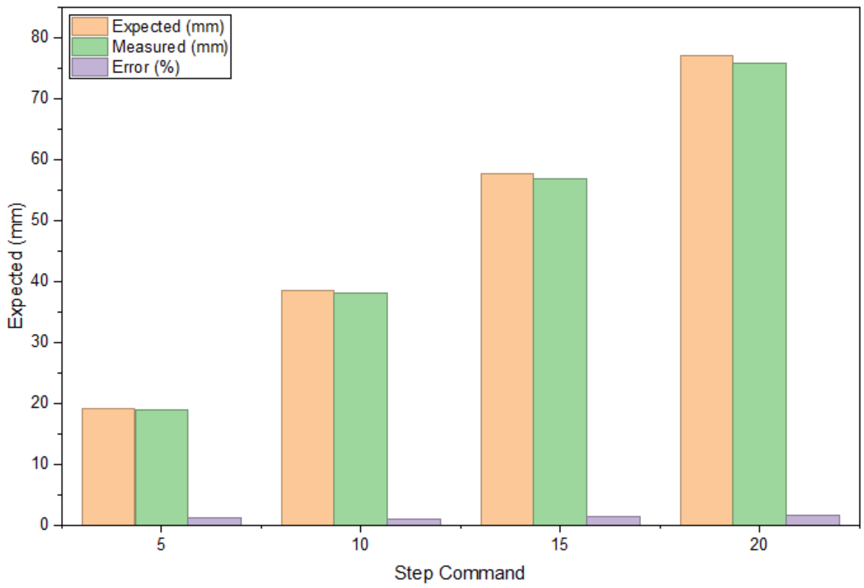


Fig. 5. Commanded vs. measured fiber feed length

Table 2. Fiber embedding accuracy for different printed pattern

| Pattern | Designed Length (mm) | Measured Length (mm) | Accuracy (%) |
|---|---|---|---|
| U-shape | 40 | 39.8 | 99.5 |
| Grid | 80 | 79.6 | 99.0 |
| Web | 120 | 118.7 | 98.9 |

The accuracy of fiber embedding was further evaluated by printing representative geometric patterns including straight paths, U-shaped trajectories, grid layouts, and web structures. Quantitative comparison between designed and measured dimensions is presented in Table 2. U-shaped patterns with a nominal length of 40 mm exhibited a measured length of 39.8 mm, corresponding to a placement accuracy of 99.5%. Grid patterns designed at 80 mm achieved an accuracy of approximately 99.0%, while larger web structures showed an accuracy of 98.9%. These results indicate that the synchronized operation of the syringe pump and CFE enables precise fiber placement even for curved and multi-directional toolpaths. The consistent placement accuracy across different geometries is attributed to the compliant silicone roller mechanism, which provides sufficient traction without inducing fiber slippage or damage, and to the accurate alignment of the fiber path beneath the hydrogel extrusion nozzle.

Table 3. Tensile properties of reinforced and non-reinforced hydrogels

| Specimen Type | Tensile Strength Increase (%) | Tensile Modulus Increase (%) |
|---|---|---|
| Reinforced Hydrogel | Up to 40 | Up to 90 |
| Non-reinforced Hydrogel | — | — |

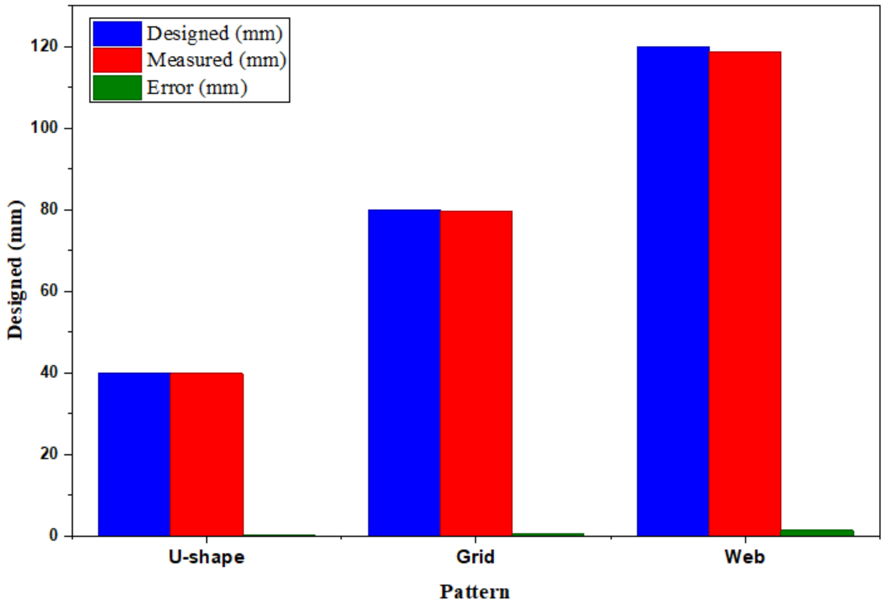


Fig. 6. Stress–strain response of hydrogel specimens

Mechanical performance of the reinforced hydrogel constructs was evaluated through uniaxial tensile testing. Stress–strain responses of reinforced and non-reinforced hydrogel specimens are compared in Fig. 6. Fiber-embedded samples exhibited a noticeable increase in stiffness, as indicated by the steeper initial slope of the stress–strain curves. The corresponding tensile strength and tensile modulus values are summarized in Table 3. Depending on the fiber material and embedding pattern, reinforced hydrogels showed up to a 40% increase in tensile strength and up to a 90% increase in tensile modulus compared to unreinforced specimens. These results confirm that continuous fiber reinforcement significantly improves load-bearing capability while retaining the compliant nature of the hydrogel matrix.

The extent of mechanical enhancement was influenced by both fiber type and embedding configuration. Biological fibers such as collagen and silk provided moderate improvements while maintaining compatibility with the hydrogel matrix, whereas synthetic and metallic fibers contributed higher stiffness due to their intrinsic material properties. Aligned and grid-based fiber layouts were particularly effective in increasing tensile modulus, as they restricted deformation and enabled efficient load transfer along the fiber direction. The observed reinforcement trends are consistent with the fundamental behavior of continuous fiber composites, where mechanical performance is governed by fiber continuity, orientation, and interfacial interaction with the matrix.

Overall, the combined results from calibration, embedding accuracy, and mechanical testing demonstrate that the developed low-cost CFE enables precise and repeatable embedding of continuous fibers within

FRESH-printed hydrogels. The close agreement between commanded and actual fiber feed lengths (Table 1 and Fig. 5), high placement accuracy across complex geometries (Table 2), and substantial improvements in tensile properties (Fig. 6 and Table 3) collectively validate the effectiveness of the proposed system. Importantly, these performance gains are achieved using a fully desktop-scale, open-source platform, highlighting the suitability of the approach for widespread adoption in reinforced hydrogel fabrication.

## 4. Conclusion

A low-cost Continuous Fiber Extruder (CFE) was successfully designed and integrated with a syringe-based hydrogel extrusion system on a desktop 3D printer for long-fiber embedded hydrogel printing using the FRESH technique. The developed system enables precise and repeatable fiber embedding using an open-source, modular platform. Calibration results showed fiber feed errors below 2%, while embedding accuracy consistently exceeded 98% across various geometric patterns. Mechanical testing confirmed the effectiveness of continuous fiber reinforcement, with reinforced hydrogels exhibiting up to 40% improvement in tensile strength and up to 90% increase in tensile modulus compared to non-reinforced samples.

The proposed approach demonstrates that significant mechanical enhancement of hydrogels can be achieved using accessible desktop hardware without compromising print fidelity. This system provides a practical pathway for reinforced hydrogel fabrication in applications such as soft robotics, bioinspired structures, and tissue engineering. Future work will focus on improving fiber–matrix interfacial bonding and extending the system to multifunctional and cell-laden hydrogel constructs.

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