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Sustainable sips: optimising ragi–sago edible ink for 3D printing eco-friendly, edible cups†

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The development of edible inks for 3D printing has gained significant attention due to its potential applications in personalized nutrition, food design, and sustainable packaging. This study focuses on the synthesis and optimization of edible ink for the 3D printing of edible cups, which can serve as an eco-friendly alternative to conventional disposable cups. The edible ink was formulated using natural food-grade materials, including polysaccharides, proteins, and plasticizers, to achieve optimal printability, mechanical strength, and biodegradability. The rheological properties of the ink were systematically optimized to ensure compatibility with extrusion-based 3D printing. The printed cups were evaluated for their mechanical properties, structural integrity, and edibility. The results indicated that the optimized ink exhibited excellent printability, with a resolution of up to 0.5 mm, and the printed cups demonstrated sufficient mechanical strength to hold liquids at room temperature. Sensory evaluation confirmed the acceptability of the cups in terms of taste and texture. This study highlights the potential of edible inks for 3D printing applications, offering a sustainable solution to reduce plastic waste while promoting innovation in food technology. Future work will focus on scaling up production and exploring additional applications in the food industry.

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Sustainability spotlight

Conventional plastic cups contribute considerably to global carbon emissions throughout their lifespan – from fossil fuel extraction to production and disposal. Our research proposes a climate-friendly alternative: 3D-printed edible cups made from ragi (finger millet) and sago starch. These plant-based cups remove petroleum reliance, minimise production energy demands, and completely biodegrade, addressing the carbon impact at every stage. The invention addresses SDG 12 (Responsible Consumption) by substituting plastic with renewable materials, SDG 13 (Climate Action) through decreased emissions, and SDG 9 (Industry Invention) *via* sustainable production. By employing drought-resistant ragi, we increase agricultural sustainability while making edible packaging that decomposes organically. This paper highlights how food technology may change packaging into a carbon-reducing, circular economy solution.

1. Introduction

The fusion of additive manufacturing or 3D printing and food science has catalyzed a paradigm shift, positioning 3D food printing as a transformative platform for crafting sustainable, personalized, and nutritionally enriched edible products.[1] Additive manufacturing (AM), has gained more and more attention as an environmentally friendly manufacturing technology because it can reduce the amount of material wasted, provide accurate control of product design, and accommodate on-demand fabrication. These benefits help lower environmental effects like resource utilization and waste production.[2] In the food sector, 3D food printing provides novel solutions towards sustainable packaging, including edible cups made from biodegradable, natural ingredients. Through combining natural food ingredients with additive manufacturing, this research moves forward the use of sustainable measures in food packaging. This technology empowers precise control over food architecture—encompassing shape, texture, and composition—offering a viable countermeasure to global challenges like plastic pollution and resource inefficiency. With over 300 million tons of plastic waste produced annually, much of it from single-use packaging,[3,4] the urgency for biodegradable alternatives is undeniable. Edible packaging, such as cups, emerges as a dual-purpose solution, blending utility with environmental stewardship. Traditional edible containers, like wafer cups and rice paper wrappers, have served niche roles for centuries, yet their reliance on conventional molding restricts design complexity and mass production potential.[5] In contrast, 3D printing unlocks boundless customization and scalability, heralding a new frontier for eco-friendly food packaging. There are many techniques involved in 3D printing under ASTM

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standards, including material extrusion, vat photopolymerization, powder bed fusion, binder jetting, and directed energy deposition. Yet, they may not be applicable in food printing because edible materials have some special demands, like biocompatibility, temperature sensitivity, and texture. Material extrusion, sometimes termed fused deposition modeling (FDM) or fused filament fabrication (FFF), is the most common technique applied in 3D food printing due to its ability to deposit food pastes or "inks" under controlled conditions at relatively low temperatures without compromising nutritional and sensory characteristics. Binder jetting and inkjet printing methods have also been adopted for food uses with capabilities of fine resolution and multi-material printing. The choice of suitable printing processes is based on the food ink's physical and chemical characteristics and the characteristics of the desired product.[6] Material extrusion-based 3D food printing is used in our research to produce edible cups from a mixture of natural ingredients, providing a scalable and viable solution to environmentally friendly food packaging. The literature on 3D food printing reflects a growing repertoire of materials, from chocolate[7] and cereal doughs[8] to hydrocolloid gels,[9] valued for their extrusion-friendly rheology. Revolutionary studies, such as, ref. 10 and 11 showcased starch-based inks for ice-creams, while ref. 12 engineered gelatin ink for edible structures. In parallel, edible packaging research has advanced, with[13,14] developing millet-starch films and[15] exploring cornstarch coatings. Yet, these studies often rely on processed or synthetic additives, sidelining traditional, minimally processed ingredients that are cost-effective, sustainable, and culturally significant. A persistent limitation remains: most edible inks lack the mechanical strength and water resistance needed for functional containers like cups; some inks have water resistant coating but those compounds are sourced from animals or insects.[16] Commercial efforts, such as Loliware's agar-based edible cups, highlight market interest but rely on costly, seaweed-derived materials less accessible in landlocked regions, underscoring the need for localized alternatives.[17] This study pioneers a novel edible ink for 3D printing cups, formulated from (i) ragi flour (derived from the grains of *Eleusine coracana*, a nutrient-dense millet widely consumed in Asia and Africa, which is rich in dietary fiber, calcium, iron, and antioxidants, making it a valuable ingredient for functional foods). Ragi flour's high starch and fiber content provide a cohesive matrix when hydrated, enabling the ink to maintain shape fidelity post-extrusion;[18,19] (ii) sago palm powder, a starchy extract from the pith of the sago palm (*Metroxylon sagu*), commonly used as a thickener in food applications across Southeast Asia. It is gluten-free and provides a neutral flavor base;[20] (iii) sesame oil extracted from *Sesamum indicum* seeds, which is a flavorful and nutrient-rich oil containing healthy fats, antioxidants, and vitamin E, and is widely used in cooking and food preservation;[21] and (iv) jaggery which is an unrefined sugar derived from sugarcane, rich in sucrose, minerals (iron and magnesium), and natural molasses, and is a traditional sweetener in South Asian cuisines; when dissolved into a syrup, jaggery acts as a natural binder, enhancing the dough's plasticity and adhesion between layers during printing.[22] All four ingredients were combined to harness their synergistic properties, effectively addressing the shortcomings of the individual components. This was followed by coating the cup with zein protein (a prolamin-type protein from corn; it is a corn-processing byproduct that is used across industries because it has some properties, *i.e.*, being biodegradable, edible, and film-forming, zein is considered a hydrophobic protein that is insoluble in water) to enhance its water resistance and overall durability.[23,24] We hypothesize that the interplay of ragi's fibrous binding, sago's starch gelation, sesame oil's lubrication, and jaggery's cohesive sweetness will yield an ink with superior printability, durability, and sensory appeal. Ragi flour anchors structural integrity, sago palm powder ensures viscosity and layer stability, sesame oil enhances flow and flavor, and jaggery binds the matrix while enriching taste and moisture retention. Unlike Loliware's niche approach, this formulation prioritizes abundant, traditional ingredients, aligning with Sustainable Development Goal 12 (Responsible Consumption and Production) by fostering circular food systems. The research aims to (1) characterize the ink's structural properties, (2) optimize its composition for extrusion-based 3D printing, and (3) evaluate the cups' functionality, durability, and consumer acceptance. Beyond reducing plastic dependency, these cups hold promise for applications in sustainable catering, disaster relief feeding programs, and rural nutrition initiatives, leveraging local resources for global impact. By the marriage of heritage ingredients with cutting-edge technology, this work fills a critical void in edible packaging and charts a scalable, sustainable culturally resonant path toward zero-waste innovation.

2. Materials and methods

Zein protein was purchased from (LOT SLBR4935V) SIGMA; [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide] (MTT ≥97.5%), was procured from Sigma-Aldrich (Bangalore, India); sago palm powder was purchased from a local shop (brand name: Sacha Moti), ragi powder was purchased from Amazon (brand name: Satvyk), flour derived from finger millet, which is naturally rich in nutrients like calcium and iron, serves as the primary base ingredient; jaggery was purchased from the local shop, and acts as a natural plasticizer along with cold-pressed sesame oil purchased from Amazon (brand name: Anveshan) which acts as a lubricant; food-grade sodium bicarbonate ($NaHCO_3$) was sourced from Himedia (cat. no. MB045); Dulbecco's phosphate buffered saline (LOT SLBZ6118), dimethyl sulfoxide acid (DMSO) (HIMEDIA, TC185) and Dulbecco's Modified Eagle Medium (DMEM) (LOT0000481561) were purchased from Himedia; Acridine Orange (AO) and ethidium bromide (EB) were acquired from Sigma-Aldrich, USA; L929 mouse fibroblasts cell lines were received from the National Centre for Cell Science (NCCS Pune, India).

2.1 Edible ink formulation

The edible ink was prepared by following a step-by-step process to get the right consistency and printability. Sago palm powder was boiled in 40 mL of water at 100 °C for 15 minutes to get fully gelatinized. At the same time a jaggery solution was prepared by boiling jaggery in 20 mL of water at 100 °C for 10 minutes until

Table 1 Edible ink formulations with weight in grams of each ingredient and water in mL

Component	Variant F1	Variant F2	Variant F3	Variant F4	Variant F5
Finger millet (g)	60 g	55 g	50 g	45 g	40 g
Sago (g)	5 g	4 g	3 g	3 g	2 g
Sesame oil (mL)	2 mL	2 mL	2 mL	2 mL	2 mL
Sodium bicarbonate (g)	0.02 g	0.02 g	0.02 g	0.02 g	0.02 g
Jaggery (g)	5 g	5 g	7 g	8 g	10 g
Water (mL)	60 mL	60 mL	60 mL	60 mL	60 mL

it got fully dissolved. Both the solutions were mixed well to get a homogeneous base. Baking soda (sodium bicarbonate) was added to the mixture and added as a dry powder to the formulation to act as a leavening agent during baking. Then 2 mL of sesame oil was added to the mixture to make it flexible and prevent cracking during printing. Finally, ragi flour was added to the mixture while stirring continuously to get the right viscosity and texture for 3D printing. The edible ink was cooled to room temperature to get a smooth and consistent formulation for extrusion-based 3D printing.

Five ink variants were prepared to test compositional effects, including baking soda. The weight in grams (g) for each component is given in Table 1, while the w/v percentage of each component is mentioned in Table 2. The w/v percentage is calculated based on the total volume of water (60 mL) as the reference volume.

2.2 3D printing process

An extrusion-based 3D customized printer (SAMUPAM, 1.55 mm nozzle) was employed. The computational design of the cup was realized by employing OpenSCAD (version 2021.01) as a parametric 3D modelling platform with the dimensional parameters optimized through formulation feasibility trials. The cup shape was modelled using constructive solid geometry operations starting with a main cylinder (51 mm high × 50 mm diameter) to model the outer shell, upon which an inner cavity (46 mm diameter) was subtracted to generate equidistant 2 mm thick walls and a 3 mm thick base. An annular stabilization element (5 mm height × 45/44 mm concentric diameters) was integrated at the base transition (*z*-offset: 3 mm) to avoid wall deformation during printing, with 78.5% material savings over solid fill and no loss of structural integrity. The parametric realization included a wall-to-base thickness ratio of 1.5 : 1 to avoid elephant foot deformation, with all circumferential geometries modelled at high resolution ($FN = 100) to provide smooth surfaces as given in Table 3 using code given in the ESI file.† This computational process provided accurate control of dimensional precision when optimizing the design for extrusion-based 3D printing with edible materials. The open-source software Pronterface (version 2.2.0) was used for printer control while PrusaSlicer (version 2.9.0) was employed for slicing the 3D models. The model was exported as an STL file, sliced using Prusaslicer to generate G-code; the parameters of the G-code are given in Table 4, the print speed was set to 70 mm min^{-1}, and the print flow rate (extrusion multiplier) was maintained at 20 mm min^{-1} to ensure dimensional stability and structural accuracy, while the nozzle temperature was set to 25 °C, and bed temperature to 75 °C. Post-printing, cups were baked using an IR lamp (40–45 min drying time) or air fryer (20–25 min drying time at 160 °C) to activate baking soda's leavening effect, enhance rigidity, and reduce moisture. Other experimental observations indicated that microwave based drying adversely affected the structural stability of the cups, likely due to rapid internal heating and moisture evaporation. Conversely, hot air oven drying (60–80 °C), though gentler, demanded prolonged exposure, which led to uneven moisture loss and compromised product uniformity.

2.3 Edible coating

After the 3D printing process was successfully achieved with the best ink composition, the second step was to coat the cups, especially the inner surface, with a hydrophobic edible coating to enhance their liquid-holding ability and durability. Two coating processes were tested: nanofiber coating and spray coating, both employing zein protein as the edible polymer. To make a 10% zein solution for spray coating, zein was dissolved in 70% ethanol. A spray bottle was filled with the solution and it was directly applied onto the inner and outer surfaces of the cup

Table 2 Formulation composition of edible ink in w/v % calculated based on the total volume of water (60 mL) as the reference volume

Component	Variant F1 (w/v%)	Variant F2 (w/v%)	Variant F3 (w/v%)	Variant F4 (w/v%)	Variant F5 (w/v%)
Ragi	100%	91.67%	83.33%	75.00%	66.67%
Sago	8.33%	6.67%	5.00%	5.00%	3.33%
Sesame oil	3.07%	3.07%	3.07%	3.07%	3.07%
Sodium bicarbonate	0.03%	0.03%	0.03%	0.03%	0.03%
Jaggery	8.33%	8.33%	11.67%	13.33%	16.67%
Water	100%	100%	100%	100%	100%

Table 3 Geometrical parameters of a 3D printed edible cup

Parameter	Value	Unit	Function	Design rationale
Height	51	mm	Total cup height (5.1 cm)	Standard teacup size for 60 mL capacity
Outer diameter	50	mm	Outer diameter of the cup	Balanced ergonomics for handheld use
Wall thickness	2	mm	Thickness of side walls	Optimized for structural stability without excess material
Base thickness	3	mm	Thickness of the base	1.5× wall thickness prevents "elephant foot" deformation during printing
Inner diameter	46	mm	Inner cavity diameter (outer diameter − 2 × wall_thickness)	Ensures uniform wall thickness
Support height	5	mm	Height of the internal stabilization ring	Prevents wall collapse during printing
Support diameter	44	mm	Inner diameter of the support ring	Creates a hollow reinforcement (material efficiency)
Coordinates				
[0,0,0]	—	mm	Origin point (centre of the base)	Aligns the model with a printer build plate
[0,0,base thickness]	—	mm	*Z*-offset for the support ring (3 mm above the base)	Positions reinforcement at the critical stress point

immediately after the printing process was over *i.e.* when the cup was not dried, and a second coating was applied once the cup was dried; so the overall coating was applied twice before drying and after drying. The coated cups were then dried under an IR lamp for 5–10 minutes to promote adhesion and curing. For nanofiber coating, a 15% zein solution was obtained by dissolving zein in glacial acetic acid. The solution was electrospun with the following parameters: 20 kV voltage potential, 10 cm collector distance from the spinneret, and a flow rate of 0.4 mL h^{-1}. Coating was performed for 15 minutes to produce a uniform nanofiber layer over the cup surface. The coated cups were then evaluated for their water retention by filling them with 60 mL of water and checking for leakage over time. The non-coated cups served as controls for comparison. According to the performance, the optimum coating technique was chosen to be used further.

2.4 Characterization

2.4.1 Edible ink selection. Choosing the right edible ink is key to 3D printing edible cups. In this study, we prepared various concentrations and compositions of edible ink using food-grade materials. We tested these formulations using a food-grade 3D printer (SAMUPAM) to evaluate printability, extrusion consistency, layer adhesion and post-printing stability. Based on the viscosity, flow behavior and mechanical strength the best ink formulation was selected. The aim is to find the ink that balances ease of printing with structural integrity and edibility.

2.4.2 Dissolution studies. To test the dissolvability of the edible cups, both spray and nanofiber-coated and non-coated sections (weighing 50 mg each) of cups were tested. The coated section was coated with a thin layer of edible coating (zein based spray or nanofiber) and the non-coated section was the control. For the dissolution test, each section was fully submerged in water at room temperature. The dissolution was monitored over time to see the rate of disintegration and structurality of the cups such as how the spray or nanofiber coating delayed the dissolution, how well the coated areas held their shape and structure compared to the non-coated areas, and how much time it takes for the cup areas to fully dissolve in water.

2.4.3 Structural integrity. Shape fidelity was assessed visually. Load-bearing capacity was tested by filling cups with water (60 mL) and monitoring leakage over 30 minutes.

2.4.4 Morphological studies. External appearance and porosity were evaluated *via* scanning electron microscopy (Carl-Zeiss-Ultra Plus Field Emission-Electron Microscopy). The samples were gold-sputtered using a Denton gold sputter unit for 30 s and the surface morphology of the samples were examined using a scanning electron microscope at 10-15 EHT under high vacuum conditions.

2.4.5 Thermogravimetric analysis. Thermogravimetric analysis (TGA) was performed with a TG/DTA SII 6300 EXSTAR thermal analyzer to analyze the thermal stability of ragi, sago, jaggery, zein, and their composite for edible cup applications. The experiment was performed up to 800 °C at a 10 °C min^{-1}

Table 4 PrusaSlicer parameters for the 3D printing process

Category	Parameter	Value/description
Layer settings	Layer height	0.8 mm
	First layer height	0.8 mm
	Vertical shells – perimeters	2 mm
	Horizontal shells – bottom solid layers	2 mm
Skirt	Loops	2
	Distance from skirt	2 mm
	Skirt height	1 mm

constant heating rate under a flowing air atmosphere (200 mL min^{-1}). This method gives information about the thermal decomposition behavior, volatile loss, and stability of the material.

2.5 Cell culture

L929 cells (mouse fibroblast cell lines, NCCS Pune) were cultured in DMEM with 10% fetal bovine serum (FBS) and 1% penicillin–streptomycin at 37 °C in a humid incubator with 5% CO_2. Media was changed every other day. After 48 h, cells were subcultured and collected using 0.25% trypsin–EDTA from sub confluent cultures (70–80%).

2.5.1 . Cytotoxicity assay. The cytotoxicity of edible cups was tested using the direct and indirect MTT assay on L929 mouse fibroblast cell lines, a common model for biocompatibility testing. Edible cups were made from food-grade materials like finger millet, zein, jaggery, zein, sodium bicarbonate and sago. The cups were sterilized, cut into small pieces (5 mg) and incubated in 5 mL cell culture medium (DMEM) at 37 °C for 24 hours in a 6-well plate to get the extract.[25] The extract was filtered through 0.22 μm syringe filter and stored at 4 °C until use. L929 cells were cultured in DMEM supplemented with 10% fetal bovine serum (FBS) and 1% penicillin–streptomycin and maintained at 37 °C in a humidified atmosphere with 5% CO_2. For the assay, cells were seeded in 96-well plates at a density of 1×10^4 cells per well and allowed to adhere for 24 hours. After adhesion, the culture medium was added with 100 μL of edible cup extract. Cells treated with culture medium only served as the negative control. In another experimental group, a zein spray coated film and zein nanofiber (5 mg each) were UV sterilised and washed with DPBS twice and then it is directly seeded in 6 well-plates after that cells had been seeded at a density of 1×10^5 with DMEM medium and incubated for 24 hours. Then both plates were incubated for 24 hours at 37 °C, and then 100 μL of MTT solution (1 mg mL^{-1} in PBS) was added to each 96-well plate and 200 μL of MTT solution to the 6-well plate. After this the plates were incubated for another 4 hours. The formazan crystals formed were dissolved by adding 100 and 200 μL of DMSO to the 96 well plate and 24 well plate respectively. Finally, the absorbance was read at 570 nm using a microplate reader (Epoch). Cell viability was calculated by using the formula (absorbance of the test sample − absorbance of blank/absorbance of the control − absorbance of blank) × 100.[26] The results were expressed as mean ± standard deviation (SD) of triplicate experiments and statistical analysis was performed using one-way ANOVA using a graph pad.

2.5.2 . Live and dead cell assay. The impact of the edible cup composite material (zein coated with jaggery/without jaggery; uncoated with jaggery and without jaggery; zein film; zein nanofiber) on the viability of L929 cells was studied by dual Acridine Orange/ethidium bromide (AO/EB) staining assay.[27] The same seeding protocol using a 96 well plate as well as the introduction of the material was performed here. After an incubation period of 24 hours, the media was removed and 10 μL of AO/EB (1 μg mL^{-1}) staining dye was added to the well and incubated for 5 min in the incubator. Stained cells were further washed using fresh PBS to remove unstained dye. Additionally, stained cells were visualized through an inverted fluorescence microscope (EVOS M5000 cell imaging system, Life technologies, USA) with related fluorescent filters at 20× magnification while it is in PBS solution.

3. Results and discussion

3.1 Printability assessment

The five formulations (F1 to F5) were tested for their applicability in 3D printing edible cups. Formulation F4 was found to be the best, showing good printability and stability during the printing process. Formulation F1 was too rigid and dense and could not be extruded through the nozzle. Formulation F2

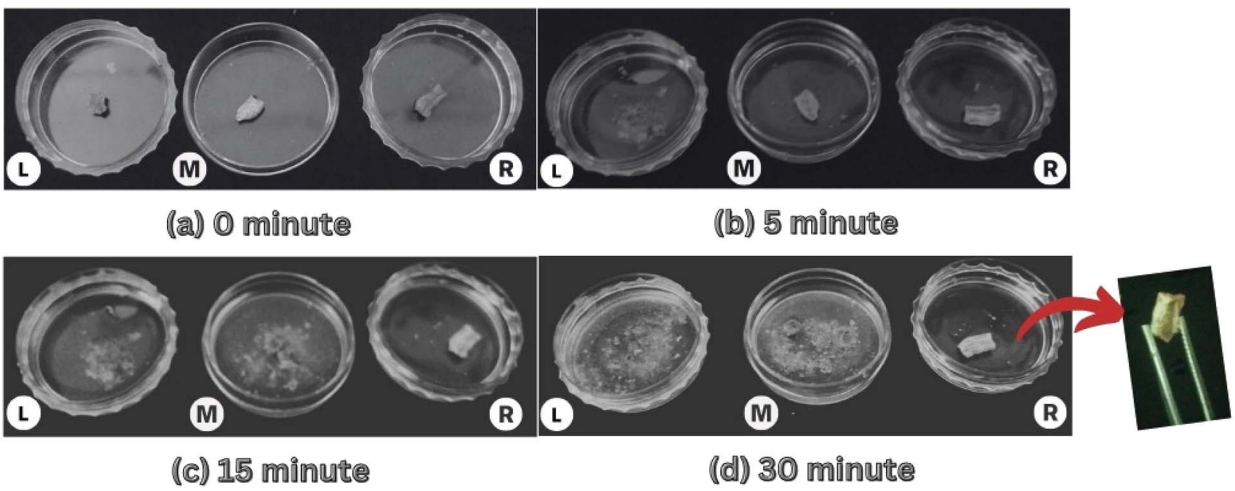

Fig. 1 Time-lapse images of the dissolution behavior of edible cup sections in water: (a) 0 minutes, (b) 5 minutes, (c) 15 minutes, and (d) 30 minutes. The sections are non-coated (L), nanofiber-coated (M), and zein spray-coated (R) regions. The non-coated section (L) broke down entirely within 5 minutes, whereas the nanofiber-coated section (M) was intact for a maximum of 10–11 minutes. The zein spray-coated sample (R) showed maximum resistance to dissolution and retained structural integrity for more than 30 minutes.

showed extrusion problems, with the filament breaking at regular intervals during printing, resulting in incomplete layer deposition. Formulation F3 exhibited better extrusion and passed the printing process but suffered cracks during the drying process, affecting structural integrity as shown in Fig. 2(a–c). Formulation F5 produced an ink too thin in viscosity, leading to fast extrusion and instability, with resultant failures during printing shown in Fig. 2(h and i). Generally, formulation F4 maintained the optimum viscosity, extrusion regularity, and stability post-printing and thus was the most appropriate for 3D printing edible cups as shown in Fig. 2(d and e) before spray coating and Fig. 2(f and g) after spray coating.

3.2 Water stability evaluation

The outcomes showed great disparity in dissolution rates between the coated and non-coated samples (sample: small piece of edible cup) and also for the whole cup when submerged in water. The zein spray-coated sample showed excellent stability, lasting for more than 30 minutes without dissolving and remained stiff and did not swell, compared to the non-coated samples that dissolved entirely after 5 minutes. The nanofiber-coated samples also showed enhanced durability, withstanding up to around 10–11 minutes before dissolving, while the whole cup submerged in water also shows good stability for a zein spray coated cup compared to an uncoated and nanofiber coated cup. The results show the efficacy of the coatings in slowing dissolution and sustaining structural integrity as shown in Fig. 1 and S1.† The zein spray coating was found to be the most effective, with the greatest resistance to water exposure, followed by the nanofiber coating. This indicates that the use of edible coatings, especially zein-based sprays, can greatly improve the functional performance of edible cups in water environments.

3.3 Water holding analysis

For load-carrying capacity, the cups (non-coated, zein spray coated, and zein nanofiber coated) were filled with 60 mL of water and checked for leakage for 30 minutes. The results

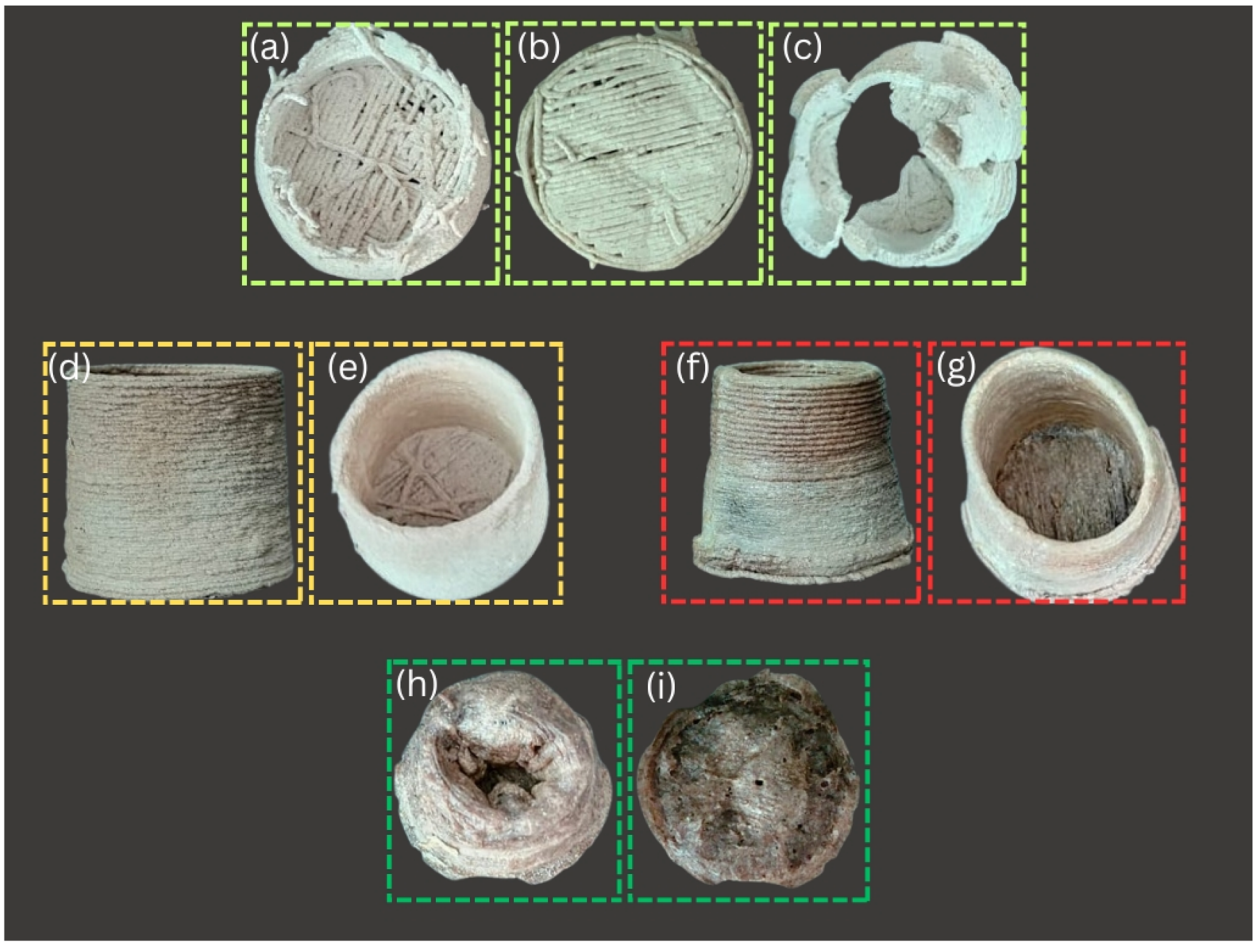

Fig. 2 Photographic images of 3D printed edible cups fabricated using different material formulations, shown in multiple orientations to highlight structural integrity and printing quality. (a–c) Edible cup printed with formulation F3, exhibiting significant cracking and structural failure after drying due to poor mechanical integrity; (d and e) cup printed with formulation F4, demonstrating excellent print fidelity and stability, shown from side and top views, respectively; (f and g) cup from formulation F4 after applying a spray coating, maintaining structural integrity with enhanced surface finish; (h and i) cup printed using formulation F5, showing severe deformation and collapse due to ink instability, as the material flowed during the drying process, resulting in loss of shape.

showed that the zein spray coated cups did not leak or deform during the test time *i.e.* 30 minutes, while the nanofiber coated cup holds water for approximately 16 minutes and non-coated cup stands for approximately 7 minutes. This shows that the spray coated cup has adequate mechanical strength to contain liquids and are thus suitable for use. The synergy between ideal ink composition and accurate printing conditions was responsible for the excellent structural integrity and functionality of the edible cup. These results highlight the viability of 3D-printed edible cups as a sustainable substitute for traditional disposable cups.

3.4 Morphological studies

The FE-SEM analysis (2500× and 5000×) demonstrates porous, layered microstructure with jaggery crystals and oil droplets embedded, suggesting successful 3D printing. Lower magnification (2500×) indicates overall uniformity, whereas higher magnification (5000×) indicates surface roughness and micro-cracks that can influence mechanical stability as shown in Fig. 3(a and b). The uniform 15 kV imaging verifies starch retrogradation and oil phase distribution essential for texture and shelf-life. The zein-coated specimens have a denser, smoother surface compared to the porous uncoated morphology, verifying successful barrier formation. Under 10 000× magnification, the coating is continuous with fewer surface defects, implying enhanced mechanical strength as depicted in Fig. 3(c). Small interfacial gaps observed under increased magnification might influence long-term stability as shown in Fig. 3(d). Ultra-high magnification (100 000×) detects the high, dense nanoscale fibrous structure in a zein film that is characteristic of the protein morphology, and lower magnification (15 000×) establishes complete homogeneous film development in the absence of defects and cracks; as illustrated in Fig. 3(e and f) the imaging indicates superior surface homogeneity, indicating ideal spray-coating conditions for barrier coatings. Nano-porosity observed at 100 000× does not necessarily impact permeability and mechanical properties of the coating. Zein nanofibers in Fig. 3(g and h) show a dense network of fibers, and the 25 000× image indicates a dense nanofiber network (~100–300 nm diameter) with homogeneous porosity, which is ideal for barrier coatings, and 100 000× demonstrates smooth, bead-free fibers, verifying optimized zein deposition. The design provides short-term stability (30–40 min) but can swell when exposed to moisture for long periods.

3.5 MTT analysis and live dead assay

The results show that both the zein film and zein nanofibers increase cell viability compared to the control, 131.44% and 111.78% respectively. This means that the zein protein is biocompatible and cell proliferative, likely due to its natural bioactive properties. Zein being a plant derived protein may provide a good microenvironment for cell adhesion and growth by providing essential amino acids or modulating cellular signalling pathways. The zein film (131.44%) has higher viability than nanofibers (111.78%) due to its denser structure which may retain more nutrients as shown in Fig. 4(a).[28] These results show zein as a biomaterial for tissue engineering, food application or drug delivery where high cell viability is crucial for success.

The cell viability assay showed that all the formulations—zein coated with jaggery (116.00%), zein coated without jaggery (114.98%), uncoated with jaggery (119.18%), and uncoated without jaggery (114.22%) exhibited higher cell viability than the control group (100%) as shown in Fig. 4(b). This is an indication of biocompatibility and the cell stimulatory effect of zein protein due to its bioactive peptides and structural support for cell adhesion in zein coated edible cups. The addition of jaggery further increased the viability (zein coated with jaggery 116.00% and 119.18% in uncoated with jaggery) which may be due to its antioxidant properties and micronutrients (iron and

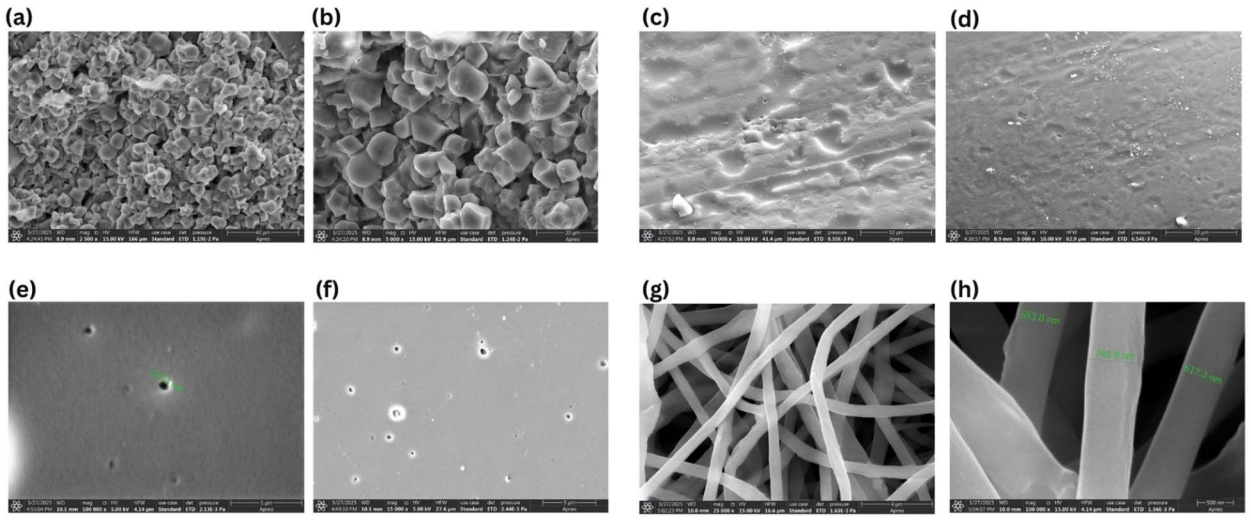

Fig. 3 SEM micrographs of 3D-printed edible cups: an (a and b) uncoated porous matrix (ragi/sago base), (c and d) zein spray-coated edible cup surface (smoother morphology), (e and f) high-res zein film nanostructure showing a dense network, and (g and h) zein nanofiber network (scale bars: a and b: 40–20 μm, c and d: 10–20 μm, e and f: 1–5 μm, and g and h: 4 μm–500 nm).

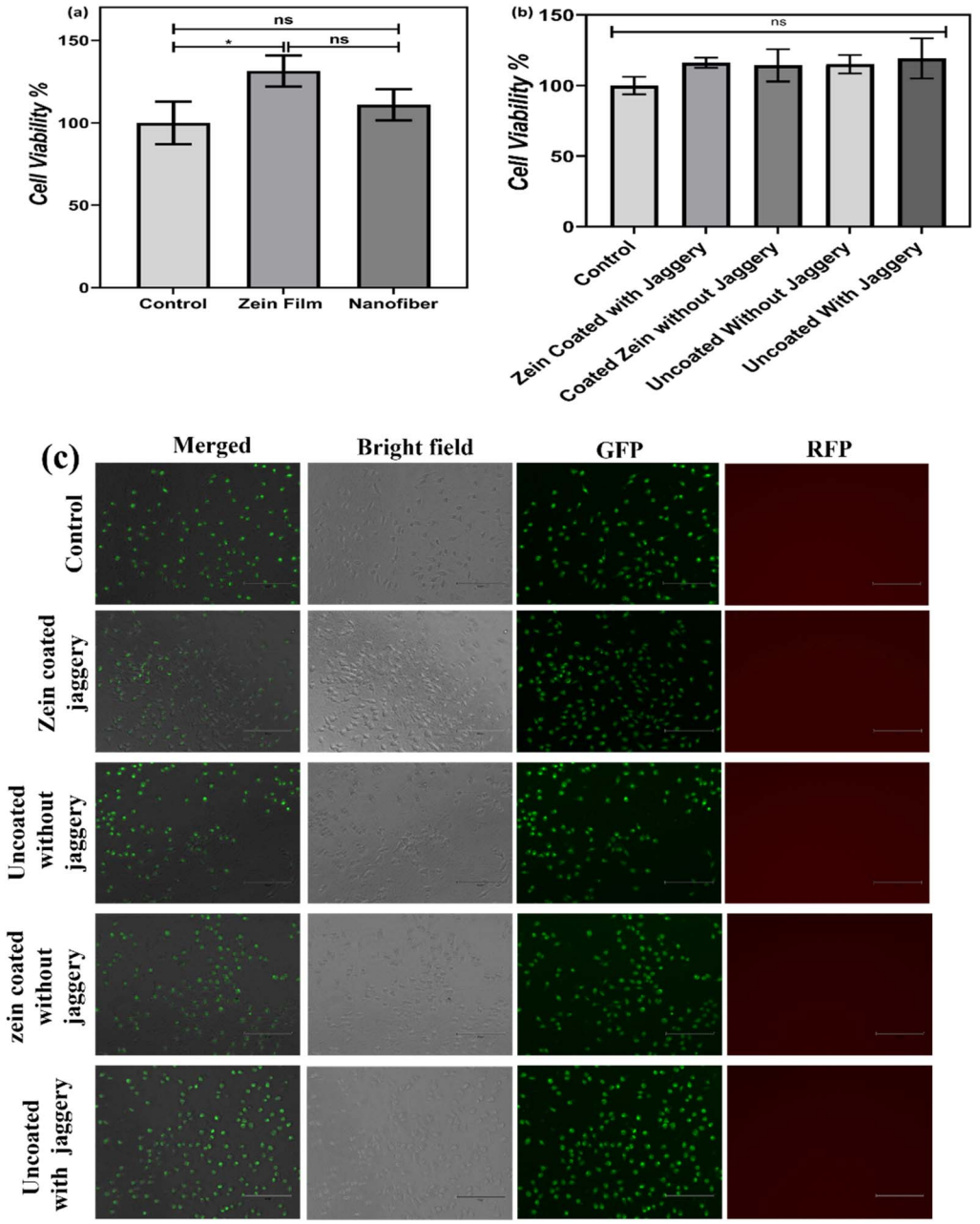

Fig. 4 (a) Cell viability (%) of the zein film and zein nanofibers *vs.* control. Both zein formulations showed more than 110% and the zein film showed the highest (131.44%) indicating inherent biocompatibility and the cell stimulatory effect of zein protein. Error bars represent mean ± SD ($n = 3$; ns: non-significant). (b) Zein coatings and jaggery supplementation on cell viability. All the formulations—zein coated (with/without jaggery) and uncoated (with/without jaggery)—showed more viability (114–119%) than the control. The highest viability (119.18%) in uncoated with jaggery indicates the synergistic effect of jaggery's, sago, and ragi. Data shown as mean ± SD ($n = 3$). (c) Comparison of fluorescence microscopy images showing GFP and RFP expression in cells under different conditions (scale bar: 150 μm).

polyphenols) that reduce oxidative stress and promote metabolic activity. Zein coated jaggery has little less viability compared to uncoated with jaggery edible cup formulation because the zein film may not allow the proper interaction of jaggery with cells. Notably, the presence of ragi, sago, sesame oil and sodium bicarbonate in all the formulations may synergistically enhance cellular nutrition and membrane stability. For example, sesame oil's unsaturated fatty acids can improve nutrient absorption, and sago and ragi can provide polysaccharides that can support extracellular matrix interactions. The live–dead cell assay further confirms the biocompatibility of the edible ink material as shown in Fig. 4(c) and S2,† where (i) merged: integrates bright field, AO, and EB images to offer a combined impression of cell morphology and viability status; (ii) bright field: reveals the cell structure and morphology under regular light microscopy; (iii) AO (live): images live cells that

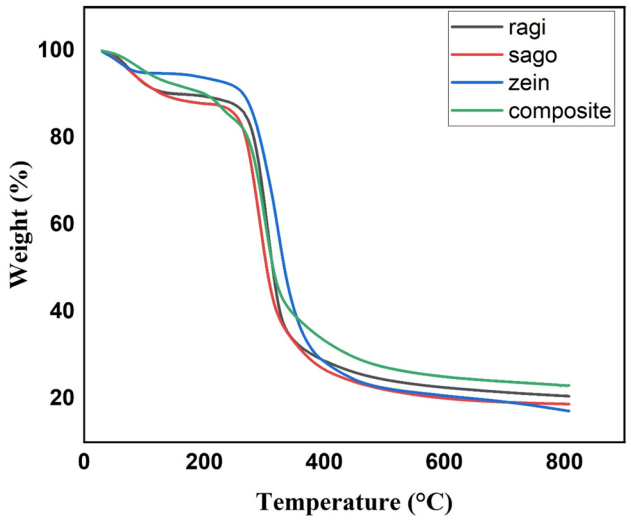

Fig. 5 Thermogravimetric characterization of ragi, sago, zein, and their composite, depicting the thermal degradation profiles and comparative stability under an air atmosphere up to 800 °C.

have been stained with Acridine Orange, which fluoresces green when it intercalates the DNA of living cells; (iv) EB (dead): indicates dead cells stained with ethidium bromide, which exhibits red fluorescence upon penetrating cells with damaged membranes and intercalating into DNA. These results suggest that zein-jaggery composites can be used as nutraceutical scaffolds or edible coatings for food applications.

3.6 Thermogravimetric assessment

The thermal behavior of ragi, sago, zein, and the formulated composite was systematically analyzed using thermogravimetric analysis (TGA) as shown in Fig. 5. In the initial heating phase below approximately 150 °C, all samples exhibited minor weight loss attributed to the evaporation of moisture. This weight loss was relatively uniform across all samples. The major decomposition phase was observed between 200 and 400 °C, marked by a sharp decline in mass. Among the individual components, zein displayed the highest onset temperature for decomposition (~270 °C), indicating greater thermal stability compared to ragi (~250 °C) and sago (~230 °C), which began degrading earlier. Notably, the composite material demonstrated a broader and more gradual weight loss profile within this range, suggesting improved thermal resistance due to the synergistic interactions between the constituent biopolymers and additives like jaggery. Beyond 400 °C, the rate of degradation slowed for all samples. The composite retained the highest residual weight at 800 °C, reflecting superior char-forming ability and enhanced thermal resistance. Sago and ragi exhibited moderate residual weights, while zein showed the least, indicating its comparatively lower thermal stability. Overall, the thermal stability of the materials followed the order composite > ragi > sago > zein. These findings highlight the composite's enhanced thermal performance, which can be attributed to the combined effect of the biopolymers and functional ingredients such as jaggery and sodium bicarbonate. This makes the composite material a promising candidate for thermally stable applications in food packaging or edible delivery systems.

4. Discussion

The creation of ingestible 3D-printed cups *via* this research illustrates effective blending of heritage ingredients with novel food production methods. Our orderly assessment of the five formulations (F1–F5) showed that formulation F4 (75% ragi, 5% sago, 3.07% sesame oil, 13.33% jaggery, and 0.03% sodium bicarbonate) attained the highest performance by resolving structural integrity *vs.* printability, confirming our initial hypothesis in terms of ingredient synergies. The rheology of F4 was especially salient. By coupling ragi flour's shear-thinning characteristics (essential for extrusion-based 3D printing) with sago's gelatinization, an ink was prepared that would flow under pressure but hold shape memory upon deposit. This is also apparent in the w/v percentages wherein the 75% ragi materiality offered adequate structural integrity while the 5% sago allowed for correct binding without unnecessary viscosity. The 3.07% sesame oil level was vital in minimizing internal friction during extrusion, as evidenced by the uniform incorporation of this percentage in all formulations. Baking soda function as a textural modifier requires specific mention. In keeping with the minimum concentration of 0.03% throughout formulations, its impact was the most effective in F4, where it achieved favorable porosity without structural sacrifice as with F5 (16.67% jaggery). This implies that the use of more than 13.33% jaggery content can cause a disturbance in the formation of CO_2 bubbles and therefore result in undesirable textures. Controlled expansion in F4 formed a cup structure possessing mechanical strength along with enjoyable mouthfeel. Relative to commercial options such as Loliware's agar-based products, our product has certain advantages in terms of cost-effectiveness and availability of material. The inclusion of ragi (75% in F4) and sago (5%) gives the product nutritional value not found in standard materials, with increased dietary fiber and mineral levels. The inclusion of 13.33% jaggery not only acts as a binder but also makes the use of other sweeteners unnecessary, giving the product a greater marketing point as a healthy option. Still, a few test challenges cropped up. The hygroscopic character of jaggery meant moisture balancing needed to be carried out very precisely, especially with high-concentration formulae (F5). In a similar manner, as 3.07% sesame oil was good for improving extrusion, use beyond that limit caused separation of the oil during initial experiments. Such experiences attest to the relevance of our finely tuned ratio-based w/v percentage table.

There are three major areas research to be targeted in the future: (i) optimization of post-printing drying procedures to preserve the structural benefits exhibited by F4; (ii) formulation of zein-based coatings to improve the hydrophobicity reported by our dissolution experiments; (iii) scaling experiments to extrapolate our laboratory achievements (based on 60 mL water as the reference volume) to industrial production levels. F4's success indicates that conventional ingredient blends, if well engineered, can satisfy the stringent requirements of 3D food

printing. By keeping the ragi content at 75% and adjusting other constituents carefully according to our w/v percentages, we had a formulation that balances printability with nutritional quality and sensory appeal. This development creates new opportunities for sustainable food packaging solutions that utilize locally sourced materials.

5. Conclusion

This research was able to successfully formulate and optimize a 3D printable food-grade ink formulation from locally available, affordable materials, with formulation F4 (75% ragi, 5% sago, 3.07% sesame oil, 13.33% jaggery, and 0.03% sodium bicarbonate) showing the best performance in printability, mechanical strength, and functional properties. The strategically optimized blend utilized the differential properties of each ingredient: ragi flour offered structural integrity through its shear-thinning nature, sago powder provided correct binding through controlled gelatinization, sesame oil optimized extrusion flow with retention of form, jaggery served as a binder and natural sweetener, and a small amount of baking soda imparted the desired porosity without loss of the structure. When contrasted with conventional commercial agar-based options, the formulation provides outstanding benefits in the areas of cost savings, accessibility of materials, and nutritional benefit, while at the same time retaining similar functional performance. Combining traditional foods with innovative processing methods offers an attractive sustainable replacement for traditional one-time use packages, especially when used in the food service sector, emergency services, and nutrition delivery systems. Future research must address scaling production, enhanced hydrophobicity *via* next-generation coatings, nutritional enrichment, and shelf-life extension. This study is an important milestone toward more sustainable packaging systems by illustrating the potential to take locally sourced materials and through deliberate formulation design and 3D printing, convert them into functional, edible structures that provide both environmental advantages and potential economic value to local communities. The discoveries are a testament to the potential of harmonizing indigenous food knowledge and new manufacturing techniques to tackle urgent global issues in waste minimization and eco-friendliness of packaging.

Data availability

The data supporting this article have been included as part of the ESI.†

Author contributions

Dravin Pratap Singh (ORCID: 0000-0002-2902-9187) designed the experiment, analyzed the data, and prepared the draft of the manuscript. Harish Ganesan Sudha (ORCID: 0009-0003-8325-9527) helped in data analysis, validation of the results, and manuscript writing. Dr Gopinath Packirisamy (ORCID: 0000-0003-1379-1203), the supervisor, provided overall guidance, experimental design inputs, and manuscript revision. All authors have read and approved the manuscript.

Conflicts of interest

The authors declare no competing financial interest.

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