

RESEARCH ARTICLE

Flowability and extrusion behavior of black soldier fly (*Hermetia illucens* L.) prepupae protein powder for three-dimensional food printing applications

Supplementary File

Table S1. Preliminary rheological screening of GG concentration and BSFP–GG base formulations for selecting the base composition used in the 3D-printable BSFP paste

Sample	BSFP (%)	GG (%)	Yield stress (Pa)	<i>K</i>	<i>n</i>	Decision
GG-0.25	–	0.25	0.15	0.12	0.55	Too weak support
GG-0.50	–	0.50	0.45	0.25	0.55	Selected balance
GG-0.75	–	0.75	1.21	0.44	0.56	High resistance
GG-1.00	–	1.00	2.12	0.70	0.58	Too stiff
B5-GG0.25	5.00	0.25	2.05	3.02	0.55	Low protein/weak support
B5-GG0.50	5.00	0.50	5.11	5.50	0.55	Extrudable but lower protein
B5-GG0.75	5.00	0.75	10.23	8.50	0.55	Stronger, lower protein
B7.5-GG0.25	7.50	0.25	8.01	8.09	0.56	Good, lower cohesion
B7.5-GG0.50	7.50	0.50	18.37	13.51	0.56	Optimum base formulation
B7.5-GG0.75	7.50	0.75	35.26	20.03	0.57	Too resistant
B10-GG0.25	10.00	0.25	30.12	19.27	0.57	High protein, resistant
B10-G0.50	10.00	0.50	55.17	30.13	0.58	High extrusion resistance
B10-G0.75	10.00	0.75	90.09	45.28	0.60	Too stiff/clogging risk

Note: GG-0.25, GG-0.50, GG-0.75, and GG-1.00 represent GG-only samples containing 0.25%, 0.50%, 0.75%, and 1.00% GG, respectively. B5, B7.5, and B10 indicate BSFP powder concentrations of 5.0%, 7.5%, and 10.0%, respectively, while GG0.25, GG0.50, and GG0.75 indicate GG concentrations of 0.25%, 0.50%, and 0.75%, respectively. *K* and *n* represent the consistency coefficient and flow behavior index, respectively.

Abbreviations: 3D: Three-dimensional; BSFP: Black soldier fly prepupae; GG: Gellan gum.

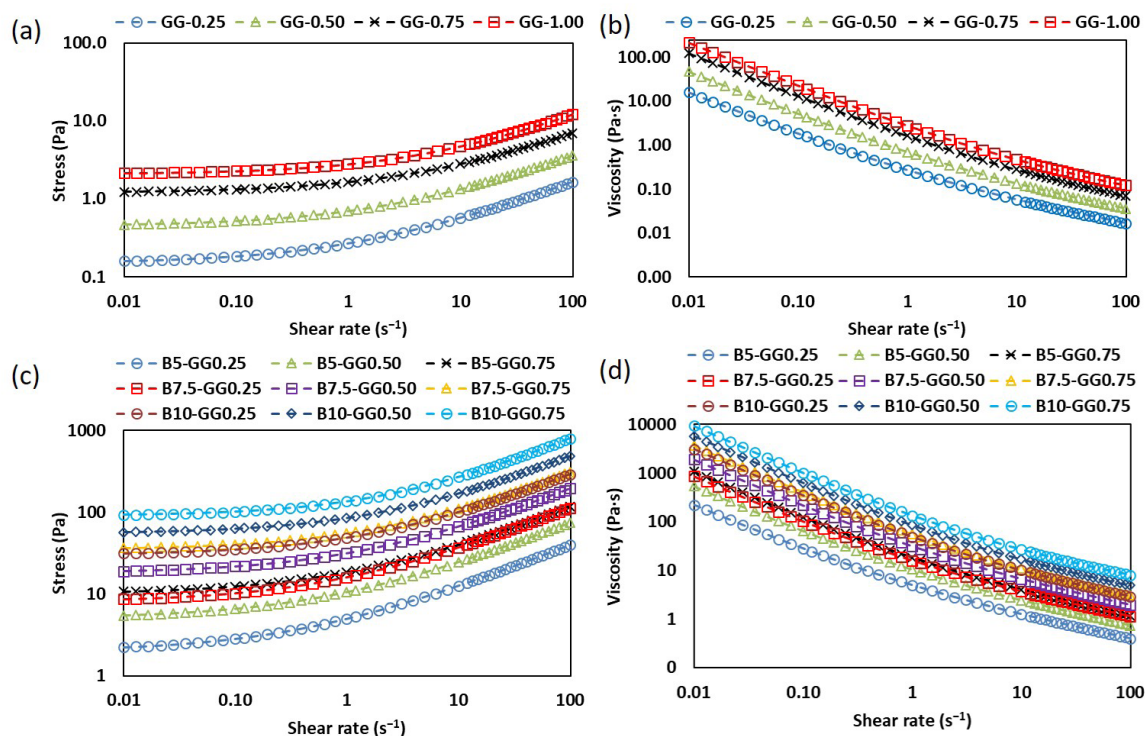


Figure S1. Preliminary rheological screening of gellan gum (GG) concentration and black soldier fly prepupae (BSFP)–GG base formulations for selecting the three-dimensional-printable paste composition. (a) Shear stress and (b) apparent viscosity of GG-only samples prepared at 0.25%, 0.50%, 0.75%, and 1.00% GG. (c) Shear stress and (d) apparent viscosity of BSFP–GG formulations prepared with different BSFP levels and GG concentrations.

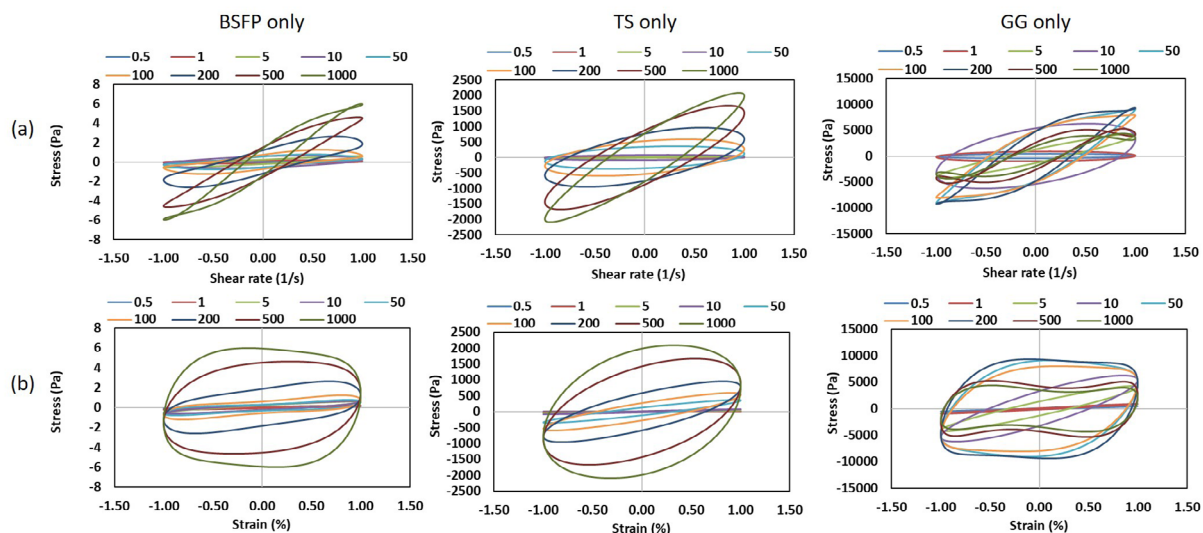


Figure S2. Large-amplitude oscillatory shear response of individual formulation components. (a) Stress–shear rate Lissajous curves and (b) stress–strain Lissajous curves of BSFP-only, TS-only, and GG-only samples measured at strain amplitudes of 0.5%–1,000%. Abbreviations: BSFP: Black soldier fly prepupae; GG: Gellan gum; TS: Tapioca starch.

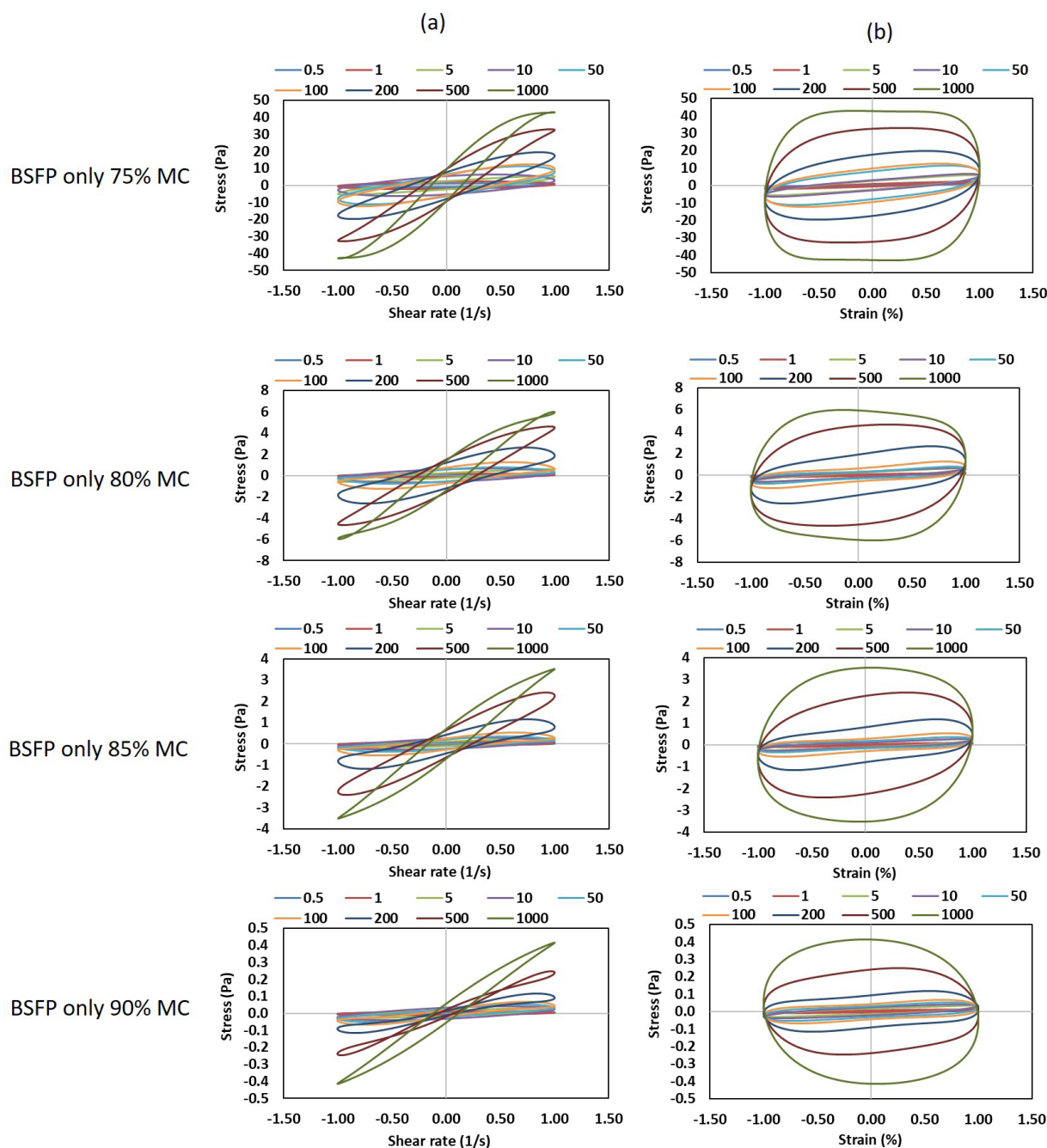


Figure S3. Large-amplitude oscillatory shear response of BSFP-only paste at different moisture contents (MCs). (a) Stress–shear rate Lissajous curves and (b) stress–strain Lissajous curves of BSFP-only samples prepared at 75%, 80%, 85%, and 90% moisture content and measured at strain amplitudes of 0.5%–1,000%.

Abbreviation: BSFP: Black soldier fly prepupae.

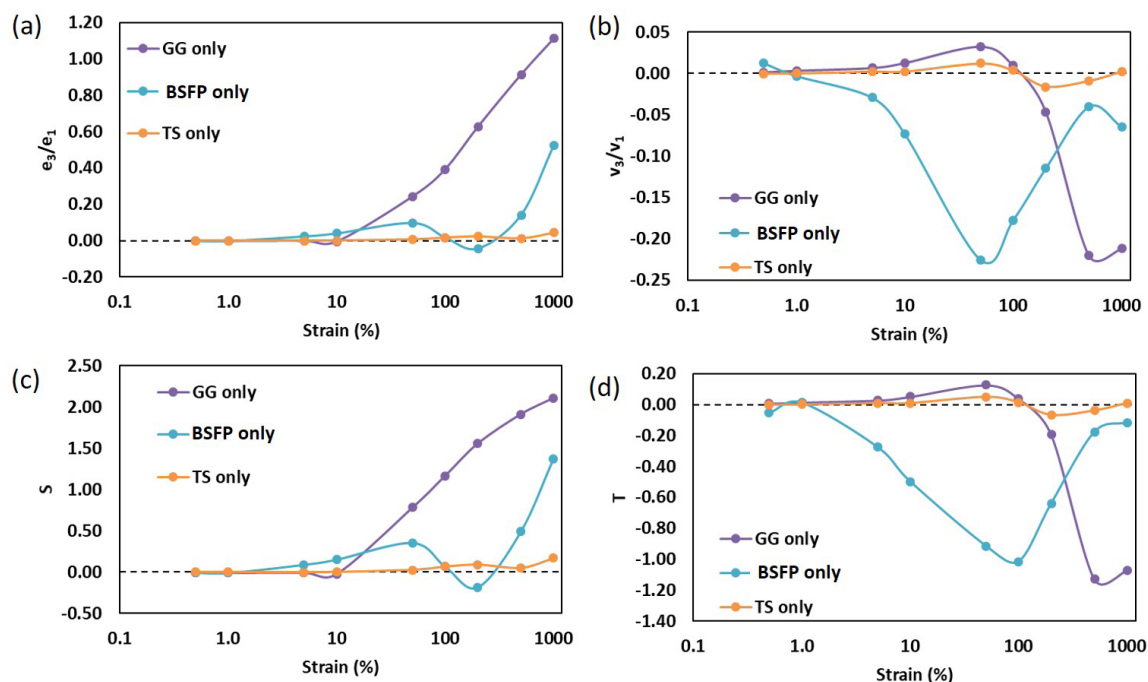


Figure S4. Chebyshev coefficient analysis of individual formulation components under large-amplitude oscillatory shear. (a) e_3/e_1 ; (b) v_3/v_1 ; (c) S , and (d) T values of GG-only, BSFP-only, and TS-only samples.

Abbreviations: BSFP: Black soldier fly prepupae; GG: Gellan gum; TS: Tapioca starch.

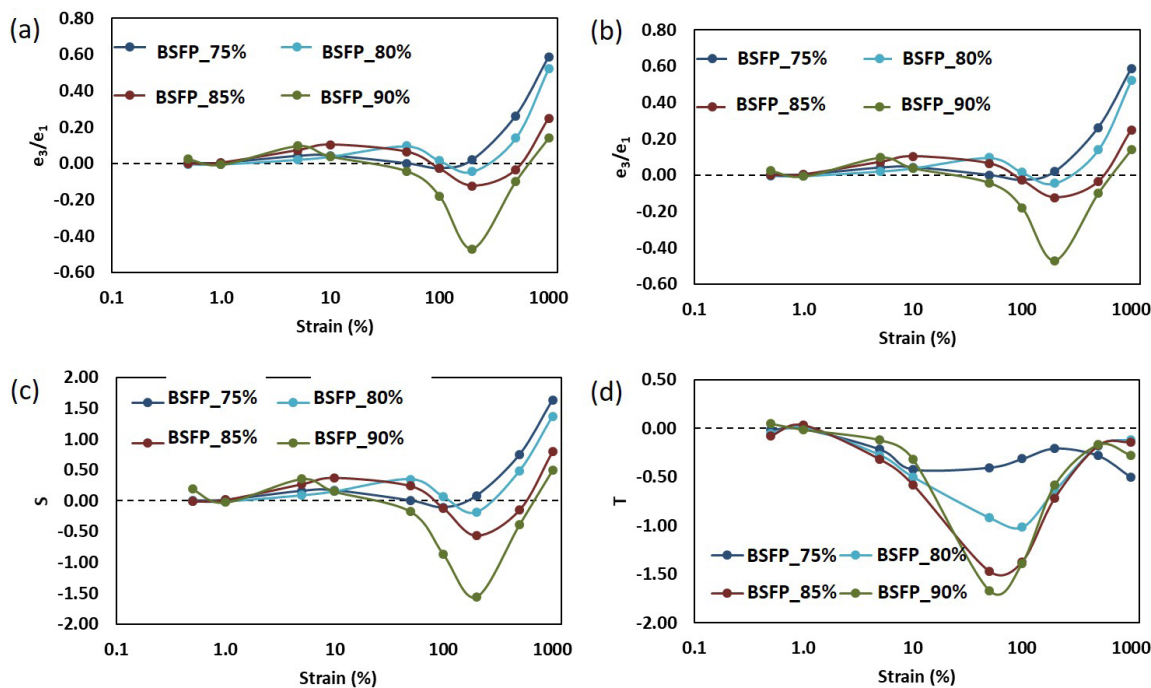


Figure S5. Chebyshev coefficient analysis of black soldier fly prepupae (BSFP)-only paste at different moisture contents under large-amplitude oscillatory shear. (a) e_3/e_1 ; (b) v_3/v_1 ; (c) S , and (d) T values of BSFP-only samples prepared at 75%, 80%, 85%, and 90% moisture content.

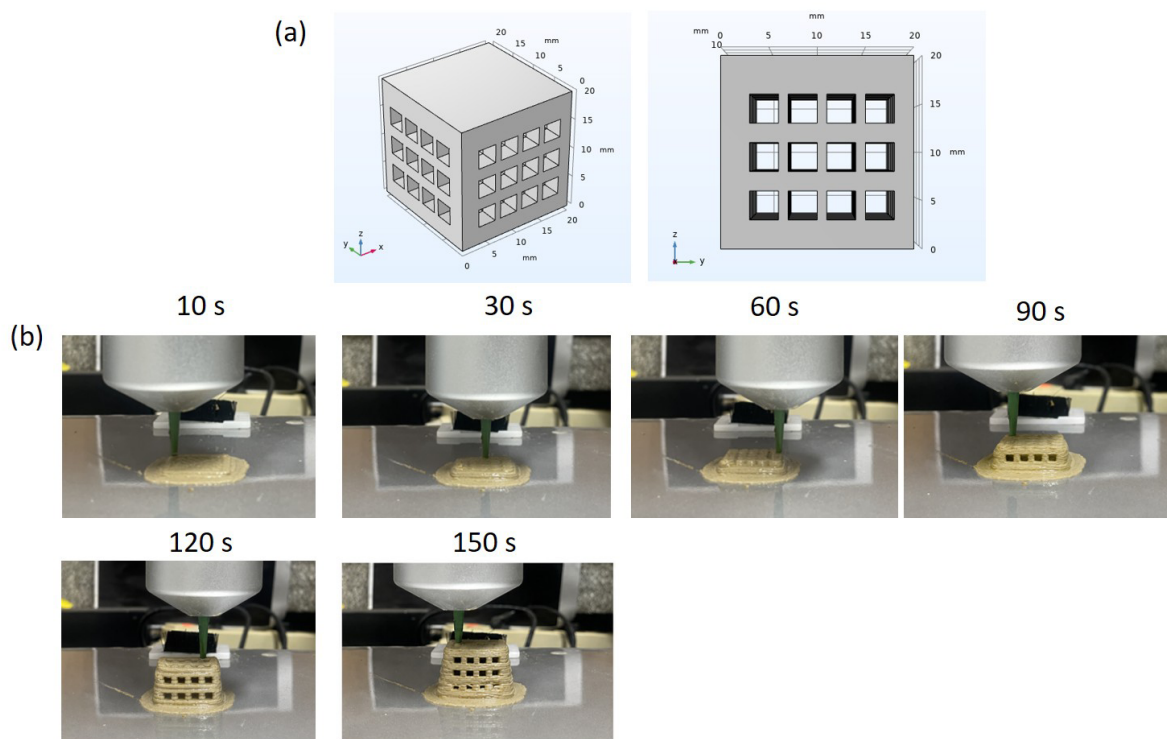


Figure S6. Validation of the direct ink writing performance of the selected BG-S2.5 formulation using a perforated $20 \times 20 \times 20$ mm box model. (a) Three-dimensional and front-view representations of the designed model. (b) Time-sequence images captured during printing.