Electronic Supplementary Material (ESI) for Food & Function.
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Electronic Supplementary Information (ESI)

Supplementary Methods

Protocol for rice couscous manufacturing

Batches of 1 kg dry materials (rice flour and maximum 10% product rework) were mixed and pre-conditioned for agglomeration in a high-speed food processor (Robot Coupe, Burgundy, France) at 800 rpm for 2 min. Water (55 to 61% of the total dry material weight) was introduced at 2.67 mL/s, under constant stirring at 800 rpm. Once the required amount of water was added, the material was agitated at 1,500 rpm for 2 min. The agglomerates were sieved in a vibratory shaker (Grain Engineering Ltd., Auckland, NZ) with a sieve size of 0.5 mm. Particles larger than 0.5 mm were used for steaming and any smaller particles were reworked into the mixing process. After 12 to 15 batches, the sieved agglomerates were spread on perforated trays lined with baking paper, and were steamed in a retort (Mauri Engineering, Palmerston North, NZ) for 20 min at 100 °C. Any lumps in the steamed agglomerates were broken by mixing (Thunderbird Food Machinery, USA) at the lowest speed setting for 30 s, followed by drying in a convection oven (INOXTREND, Italy) at 70 to 80 °C for 18 to 20 h. The dried products were sieved to remove particles with desired size range (final product, 0.5 mm $< d \leq$ 2 mm), smaller particles ($d \leq$ 0.5 mm) to be reworked to the first stage, and larger particles ($d >$ 2 mm) for additional grinding step in a hammer mill (Siemens-Schuckert, Germany). The ground particles were sieved again, and only particles within the desired size range were collected and combined with the other final product fraction.

Particle size standardization

Noodle diets (rice noodle and pasta) were cut to 60- to 70-mm length (for acclimatization period) or 30- to 40-mm length (for penultimate and final meals), both to allow the pigs to eat the noodle meals and to have a standardized initial particle size. The couscous diets were sieved with a vibrating sifter machine (Retsch, Germany) and only fractions between 0.5 to 2 mm (for acclimatization period) or 1 to 2 mm (for penultimate and final meals) were used for cooking. Larger sizes of noodle and couscous diets were used during acclimatization period to minimize wasted materials, as the objective of the acclimatization was to familiarize the pigs with the diets. The size of noodle and couscous diets used for the penultimate and final meals were within a carefully controlled size range to allow for a more precise examination of particle size changes during gastric digestion.

Cooked diets volume and bulk density determination

The volume of the cooked diets was determined using a modified water displacement method with at least eight measurements for each sample batch, using at least two batches of samples. A flat-bottom container was filled with 10 mL water and the water level was marked on the side. The volume of the diet was defined as the volume of water displaced from the marked level after addition of 5 g sample, which was determined by transferring the displaced volume to a 10-mL measuring cylinder. The bulk density of the diets was calculated by dividing the mass of the diet by the volume of the diet.

Cooked diets water holding capacity (WHC) determination

Water holding capacity (WHC) of the cooked diets in this study was defined as the maximum amount of moisture that could be held by the diets in its undigested form. WHC was measured at least in duplicate using centrifugation method.[31] Each cooked diet sample (2.5 g) was weighed in a pre-weighed centrifuge tube and mixed with 30 mL distilled water. The tubes were kept in a shaking water bath (50 rpm, 37 °C) for 4 h, then centrifuged for 20 min at 4,200 rpm, 25 °C. Each diet was removed from its tube, weighed (weight of wet sample), dried for 16 h at 105 °C, and the dry weight was recorded (weight of dried sample). The WHC of the cooked diets was defined as:

$$WHC_{diet}\ \left(\frac{g\ H_2O}{g\ DM}\right) = \frac{weight\ of\ wet\ sample}{weight\ of\ dried\ sample} - 1 \qquad (1)$$

Normalization of hardness data

In the present study, the measured hardness values of digesta samples were higher than the initial hardness of their respective diets, except for semolina, because the initial diet property measurement was done without additional lubrication. A previous study with similar carbohydrate-based foods and compression method found that cooked, undigested food particles stuck together and formed large void spaces when they were prepared for bulk compression, resulting in a lower initial hardness due to compression of air spaces.[12] To correct for void spaces in the non-lubricated particles, the initial hardness of each diet was multiplied with a correction factor calculated from published data[12] (ESI Table 3). This corrected initial hardness value was used as the H_0 in the fitting of H_t/H_0 in eqn. (5).

Supplemental Tables

Supplemental Table 1 Moisture content values of digesta from proximal and distal stomach regions over 240 min digestion (mean values ± SEM, $2 \leq n \leq 5$). Significantly different values within the same row (diet × stomach region) are represented with superscripts zyx ($p < 0.05$); significantly different values within the same column (diet × digestion time) are represented with superscripts abcd ($p < 0.05$).

Diet	Stomach region	Digestion time (min)			
		30	60	120	240
Semolina	Proximal	$5.39 \pm 0.14^{a,x}$	$5.80 \pm 0.15^{a,yx}$	$9.10 \pm 2.08^{a,zy}$	$8.70 \pm 1.09^{a,z}$
	Distal	$5.81 \pm 0.12^{a,y}$	$6.10 \pm 0.15^{a,y}$	$7.28 \pm 1.10^{a,zy}$	$9.61 \pm 1.52^{a,z}$
Couscous	Proximal	3.07 ± 0.16^{b}	3.55 ± 0.28^{b}	3.76 ± 0.28^{bc}	4.76 ± 0.51^{b}
	Distal	3.36 ± 0.16^{b}	3.86 ± 0.17^{b}	4.12 ± 0.26^{bc}	4.99 ± 0.41^{b}
Pasta	Proximal	2.54 ± 0.09^{b}	2.72 ± 0.06^{b}	3.07 ± 0.10^{bc}	3.51 ± 0.31^{b}
	Distal	2.77 ± 0.09^{b}	3.12 ± 0.07^{b}	3.44 ± 0.16^{bc}	3.83 ± 0.37^{b}
Rice Grain	Proximal	2.5 ± 0.10^{b}	2.52 ± 0.07^{b}	2.84 ± 0.18^{bc}	3.23 ± 0.29^{b}
	Distal	2.98 ± 0.16^{b}	3.01 ± 0.10^{b}	3.40 ± 0.15^{bc}	3.82 ± 0.20^{b}
Rice Couscous	Proximal	2.91 ± 0.15^{b}	3.41 ± 0.31^{b}	3.54 ± 0.10^{bc}	4.19 ± 0.32^{b}
	Distal	$2.93 \pm 0.11^{b,y}$	$3.32 \pm 0.33^{b,zy}$	$3.82 \pm 0.18^{bc,zy}$	$4.80 \pm 0.61^{b,z}$
Rice Noodle	Proximal	2.40 ± 0.11^{b}	2.69 ± 0.11^{b}	2.80 ± 0.06^{c}	3.27 ± 0.23^{b}
	Distal	2.80 ± 0.18^{b}	3.23 ± 0.16^{b}	3.64 ± 0.09^{b}	3.97 ± 0.24^{b}

Supplemental Table 2 Total moisture added and moisture addition rate to the diets (mean values ± SEM, $3 \leq n \leq 5$ for each diet × time). Significantly different values of moisture added over time for each diet are represented with superscripts abcd ($p < 0.05$)

Diet	Time (min)	Total moisture added (g)	Moisture addition rate§ (g /min)
Semolina	30	194.34 ± 43.09^{a}	6.48 ± 1.44
	60	259.61 ± 15.38^{a}	2.18 ± 0.26
	120	779.65 ± 259.01^{b}	8.67 ± 2.16
	240	1188.67 ± 150.67^{b}	3.41 ± 0.63
Pasta	30	215.25 ± 28.06	7.17 ± 0.94
	60	291.34 ± 14.05	2.54 ± 0.23
	120	379.13 ± 12.36	1.46 ± 0.10
	240	590.37 ± 114.50	1.76 ± 0.48
Couscous	30	455.45 ± 32.71^{a}	15.18 ± 1.09
	60	621.00 ± 60.05^{ab}	5.52 ± 1.00
	120	723.93 ± 82.62^{ab}	1.72 ± 0.69
	240	891.85 ± 78.02^{b}	1.40 ± 0.33
Rice Grain	30	348.35 ± 40.61	11.61 ± 1.35
	60	354.75 ± 22.77	0.21 ± 0.38
	120	438.69 ± 31.89	1.40 ± 0.27
	240	583.83 ± 36.61	1.21 ± 0.15
Rice Noodle	30	150.69 ± 28.56	5.02 ± 0.95
	60	221.40 ± 28.17	2.36 ± 0.47
	120	288.81 ± 12.78	1.12 ± 0.11
	240	461.51 ± 60.77	1.44 ± 0.25
Rice Couscous	30	267.74 ± 18.50^{a}	8.92 ± 0.62
	60	439.04 ± 88.51^{ab}	5.71 ± 1.48
	120	479.61 ± 40.00^{ab}	0.68 ± 0.33
	240	735.85 ± 92.91^{b}	2.14 ± 0.39

§Moisture addition rate,t_2 = $\frac{Moisture\ added, t_1 - Moisture\ added, t_2}{t_2 - t_1}$; t_2 = current time point (30/60/120/240 min), t_1 = previous time point (0/30/60/120 min). Moisture added at t = 0 min was assumed to be zero.

Supplemental Table 3 Correction factor calculation for correcting the effect of lubrication on H_0. Data at 33 and 67% bulk compression strain were obtained from Drechsler and Bornhorst.[12]

Compression strain (%)	Lubricating agent	Hardness with lubrication: hardness without lubrication ratio				
		Brown Rice	Couscous	Orzo	Quinoa	White Rice
33	Water	2.00	2.61	4.18	1.53	1.50
	NES§	2.26	2.19	2.87	1.26	1.87
67	Water	1.75	2.01	3.71	2.27	0.97
	NES§	1.73	1.67	3.45	1.93	1.10
Approximated correction factor at 50% strain						
50	Water	1.88	2.31	3.94	1.90	1.24
	NES§	1.99	1.93	3.16	1.60	1.49
Average correction factor (Water and NES lubricated)		1.94	2.12	3.55	1.75	1.36
Averaged overall correction factor				**2.14**		

§NES: simulated saliva that contained mucins, without salivary enzymes.

Supplemental Table 4 Hardness and normalized hardness values of undigested cooked diets and gastric digesta from proximal and distal stomach regions over 240 min digestion (mean values ± SEM, 4 ≤ n ≤ 6) used for Weibull model fitting. For the digesta data (30 to 240 min), significantly different values within the same row (diet × digestion time) are represented with superscripts abcd; significantly different values of within the same column (diet × stomach region) are represented with superscripts zyx (*p* <0.05).

Hardness (N)

Diet	Semolina		Couscous		Pasta		Rice Grain		Rice Couscous		Rice Noodle	
Time (min)	Proximal	Distal	Proximal	Distal	Proximal	Distal	Proximal	Distal	Proximal	Distal	Proximal	Distal
0*	5.51 ± 1.47		52.09 ± 7.10		29.40 ± 5.13		66.71 ± 6.40		67.24 ± 7.82		38.80 ± 1.30	
30	0.76 ± 0.20^{e}	0.70 ± 0.16^{e}	$14.56 \pm 2.50^{bc,z}$	7.80 ± 0.76^{cde}	22.62 ± 2.93^{b}	21.28 ± 1.96^{bc}	$39.63 \pm 5.57^{a,z}$	$42.87 \pm 1.89^{a,z}$	1.17 ± 0.40^{de}	1.22 ± 0.36^{de}	12.88 ± 3.64^{bcde}	23.66 ± 4.02^{b}
60	0.45 ± 0.06^{d}	0.30 ± 0.04^{d}	$9.99 \pm 2.55^{cd,zy}$	3.01 ± 0.25^{d}	20.42 ± 1.08^{bc}	18.76 ± 3.22^{bc}	$38.68 \pm 4.14^{a,zy}$	$30.88 \pm 1.26^{ab,zy}$	1.16 ± 0.63^{d}	0.53 ± 0.11^{d}	8.29 ± 1.75^{cd}	11.35 ± 1.52^{cd}
120	0.27 ± 0.07^{f}	0.25 ± 0.06^{f}	$9.39 \pm 2.20^{cdef,zy}$	2.47 ± 0.30^{ef}	14.94 ± 2.65^{bc}	14.90 ± 1.67^{bc}	$24.19 \pm 3.08^{b,y}$	$35.21 \pm 3.01^{a,zy}$	6.32 ± 3.60^{cdef}	2.56 ± 1.44^{df}	7.87 ± 1.58^{cdef}	14.17 ± 1.43^{bce}
240	0.19 ± 0.04^{c}	0.16 ± 0.02^{c}	$1.19 \pm 0.57^{c,y}$	1.77 ± 0.85^{c}	11.14 ± 1.49^{bc}	9.04 ± 1.85^{bc}	$21.93 \pm 2.54^{ab,y}$	$26.38 \pm 3.05^{a,y}$	6.45 ± 3.57^{c}	3.78 ± 1.87^{c}	4.78 ± 1.66^{c}	9.65 ± 2.73^{c}

Normalized hardness, H_t/H_0

Diet	Semolina		Couscous		Pasta		Rice Grain		Rice Couscous		Rice Noodle	
Time (min)	Proximal	Distal	Proximal	Distal	Proximal	Distal	Proximal	Distal	Proximal	Distal	Proximal	Distal
0	1.00		1.00		1.00		1.00		1.00		1.00	
30	0.14 ± 0.04^{de}	0.13 ± 0.03^{de}	0.28 ± 0.05^{cde}	0.15 ± 0.01^{de}	$0.68 \pm 0.04^{a,zy}$	$0.72 \pm 0.07^{a,z}$	0.6 ± 0.09^{ab}	0.58 ± 0.07^{ab}	0.33 ± 0.01^{c}	0.02 ± 0.01^{e}	0.33 ± 0.09^{bcd}	0.50 ± 0.14^{abc}
60	0.09 ± 0.01^{d}	0.05 ± 0.01^{d}	0.19 ± 0.05^{cd}	0.06 ± 0.005^{d}	$0.69 \pm 0.04^{a,z}$	$0.53 \pm 0.04^{ab,zy}$	0.58 ± 0.06^{a}	0.46 ± 0.02^{abc}	0.21 ± 0.01^{d}	0.01 ± 0.001^{d}	0.21 ± 0.05^{cd}	0.29 ± 0.04^{bcd}
120	0.05 ± 0.01^{c}	0.04 ± 0.01^{c}	0.18 ± 0.04^{bc}	0.05 ± 0.01^{c}	$0.58 \pm 0.06^{a,zy}$	$0.51 \pm 0.06^{a,zy}$	0.41 ± 0.06^{ab}	0.53 ± 0.05^{a}	0.20 ± 0.05^{c}	0.04 ± 0.02^{c}	0.20 ± 0.04^{bc}	0.39 ± 0.04^{ab}
240	0.03 ± 0.01^{bc}	0.03 ± 0.004^{bc}	0.02 ± 0.01^{c}	0.03 ± 0.02^{bc}	$0.38 \pm 0.05^{a,y}$	$0.31 \pm 0.06^{abc,y}$	0.33 ± 0.04^{ab}	0.40 ± 0.05^{a}	0.12 ± 0.06^{abc}	0.06 ± 0.03^{bc}	0.12 ± 0.04^{abc}	0.25 ± 0.07^{abc}

*Initial hardness of the diet multiplied with the correction factor of 2.14 (see Supplemental Table 3).

Supplemental Table 5 Weibull kinetic parameters (estimated with eqn. (6)) and softening half-time of the experimental diets in the proximal and distal stomach regions. Each parameter is presented as predicted parameter ± 95% confidence interval.

Diet	**Stomach region**	**Weibull model parameter**		**R^2**	**Softening half-time, $t_{1/2,\ softening}$ (min)**
		m **(× 10^2 min^{-1})**	**γ (dimensionless)**		
Semolina	Proximal	37.50 ± 97.10	0.28 ± 0.28	0.96	0.7
	Distal	41.64 ± 110.65	0.30 ± 0.30	0.97	0.7
Couscous	Proximal	6.18 ± 6.01	0.36 ± 0.25	0.82	5.9
	Distal	22.98 ± 28.76	0.35 ± 0.20	0.98	1.5
Pasta	Proximal	0.33 ± 0.19	0.53 ± 0.26	0.66	151.9
	Distal	0.51 ± 0.22	0.56 ± 0.25	0.67	101.2
Rice Grain	Proximal	0.55 ± 0.35	0.41 ± 0.26	0.53	74.5
	Distal	0.20 ± 0.38	0.20 ± 0.21	0.51	79.9
Rice Couscous	Proximal	98.82 ± 2331.58	0.26 ± 1.95	0.67	0.3
	Distal	75.70 ± 5698.60	0.41 ± 12.15	0.93	0.5
Rice Noodle	Proximal	5.55 ± 7.62	0.28 ± 0.25	0.67	4.9
	Distal	1.42 ± 1.30	0.25 ± 0.29	0.43	16.6

Supplemental Table 6 Goodness-of-fit of Weibull and gastric emptying models for the averaged values of the experimental data (normalized hardness data for Weibull model, gastric digesta mass retention for gastric emptying models).

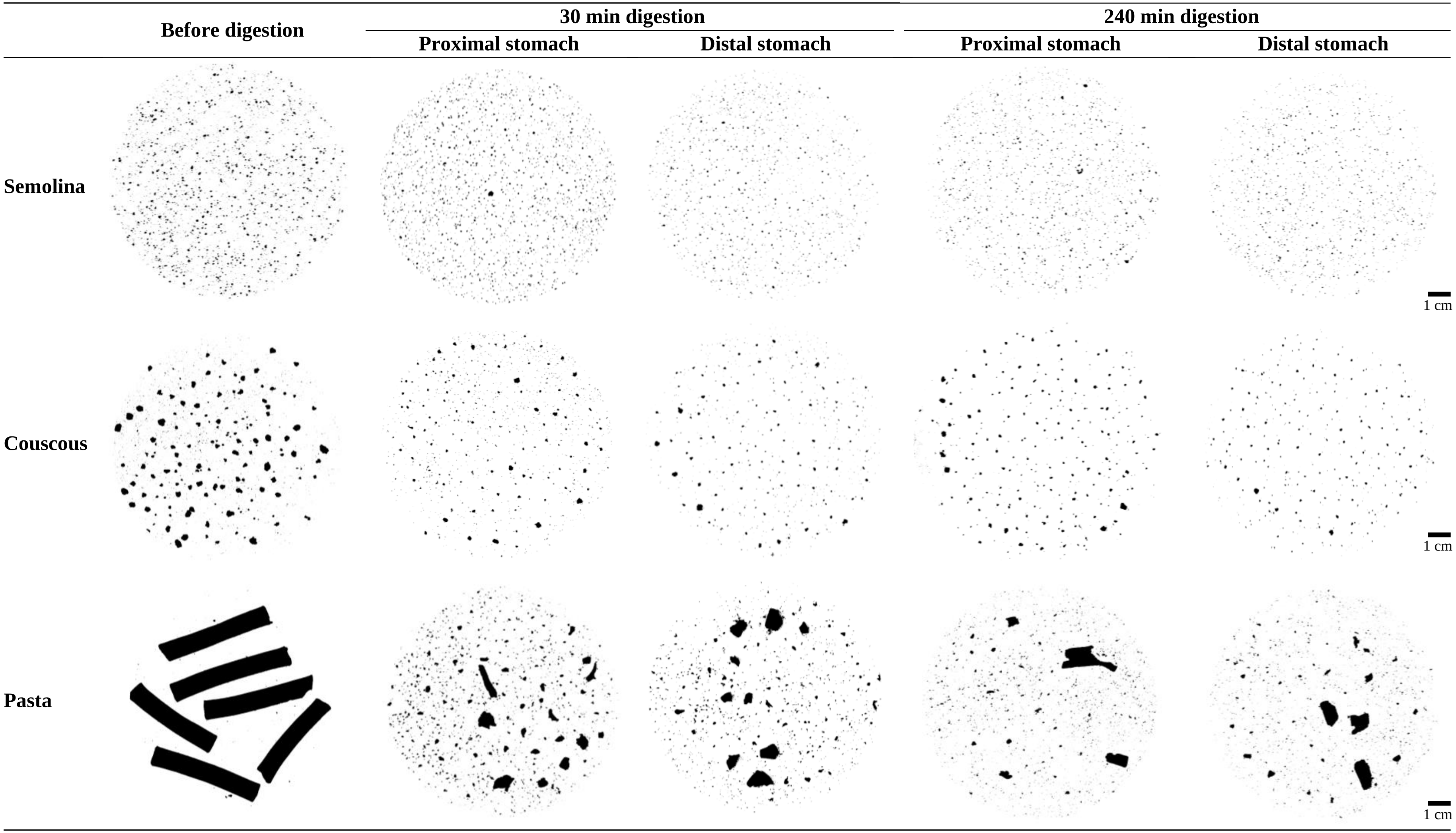
Diet	R^2 Weibull model		R^2 DM emptying model	R^2 whole stomach content emptying model
	Proximal stomach	Distal stomach		
Semolina	1.00	1.00	0.99	0.96
Couscous	0.99	1.00	0.99	0.91
Pasta	0.99	1.00	1.00	0.94
Rice Grain	0.99	0.97	0.99	0.76
Rice Couscous	0.96	0.96	0.98	0.93
Rice Noodle	1.00	0.96	0.99	1.00

Supplemental Table 7 Statistical significance from mixed model ANOVA of diet type, digestion time, stomach region, and their interactions on the properties of gastric digesta and gastric emptying.

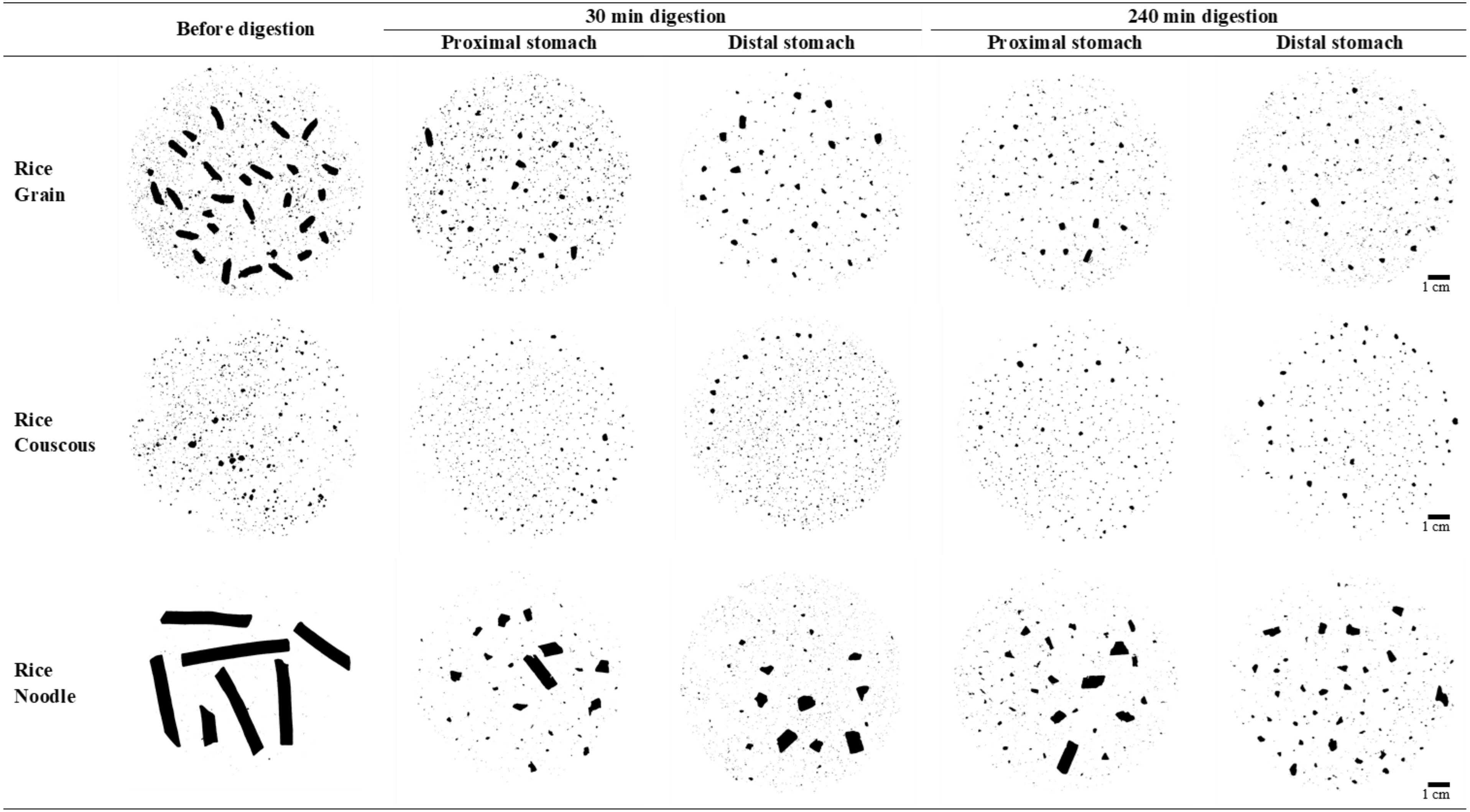
Parameter	*p*-value							
	Diet	Time	Region	Diet × Time	Diet × Region	Region × Time	Diet × Region × Time	Pig Group
Digesta properties								
MC,db	****	****	****	*	*	NS	NS	**
SR	****	****	****	NS	****	NS	NS	**
pH	NS	****	****	***	****	****	**	****
x_{10}	****	*	NS	NS	NS	NS	NS	****
x_{50}	****	*	***	NS	**	NS	NS	***
x_{90}	****	NS	**	NS	****	NS	NS	*
b	****	***	NS	NS	**	NS	NS	****
Particles/g DM	****	NS	NS	NS	NS	NS	*	****
Stress at 0.2 s^{-1}	****	****	****	****	***	NS	NS	NS
Yield stress	****	****	NS	****	NS	*	NS	***
K	****	****	****	****	**	*	NS	NS
n	****	**	NS	NS	NS	***	**	NS
G' 1 Hz	****	****	****	****	**	***	*	NS
G" 1 Hz	****	****	****	****	****	****	**	NS
tan(δ)	****	NS	NS	****	****	NS	*	NS
Hardness	****	****	NS	***	****	NS	**	NS
Gastric emptying								
Dry matter	****	****	-	NS	-	-	-	NS
Whole stomach content	****	****	-	*	-	-	-	NS

MC, db: moisture content (dry basis); SR: saturation ratio; x_{10}, x_{50}, x_{90}: 10^{th}, 50^{th}, 90^{th} percentile of the particle areas; *b*: broadness of particle area distribution; Particles/g DM: particles per gram dry matter; *K*: consistency index; *n*: flow index; *G*' 1 Hz: storage modulus measured at 1 Hz; *G"* 1 Hz: loss modulus measured at 1 Hz; %DM: percentage of dry matter left in the stomach.
Asterisk (*) symbols indicate different levels of statistical significance. *: $p < 0.05$; **: $p < 0.01$, *** : $p < 0.001$, ****: $p < 0.0001$. NS: not significant.

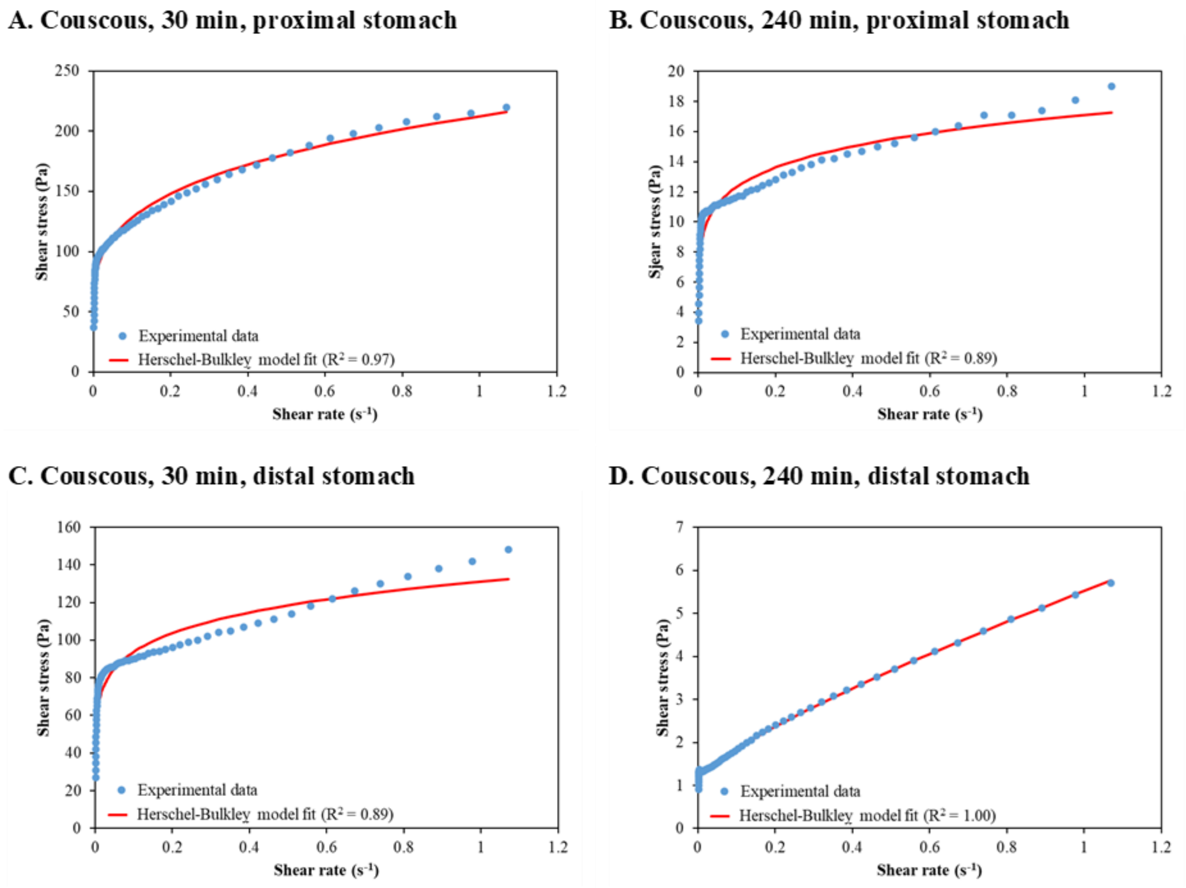
Supplemental Figures



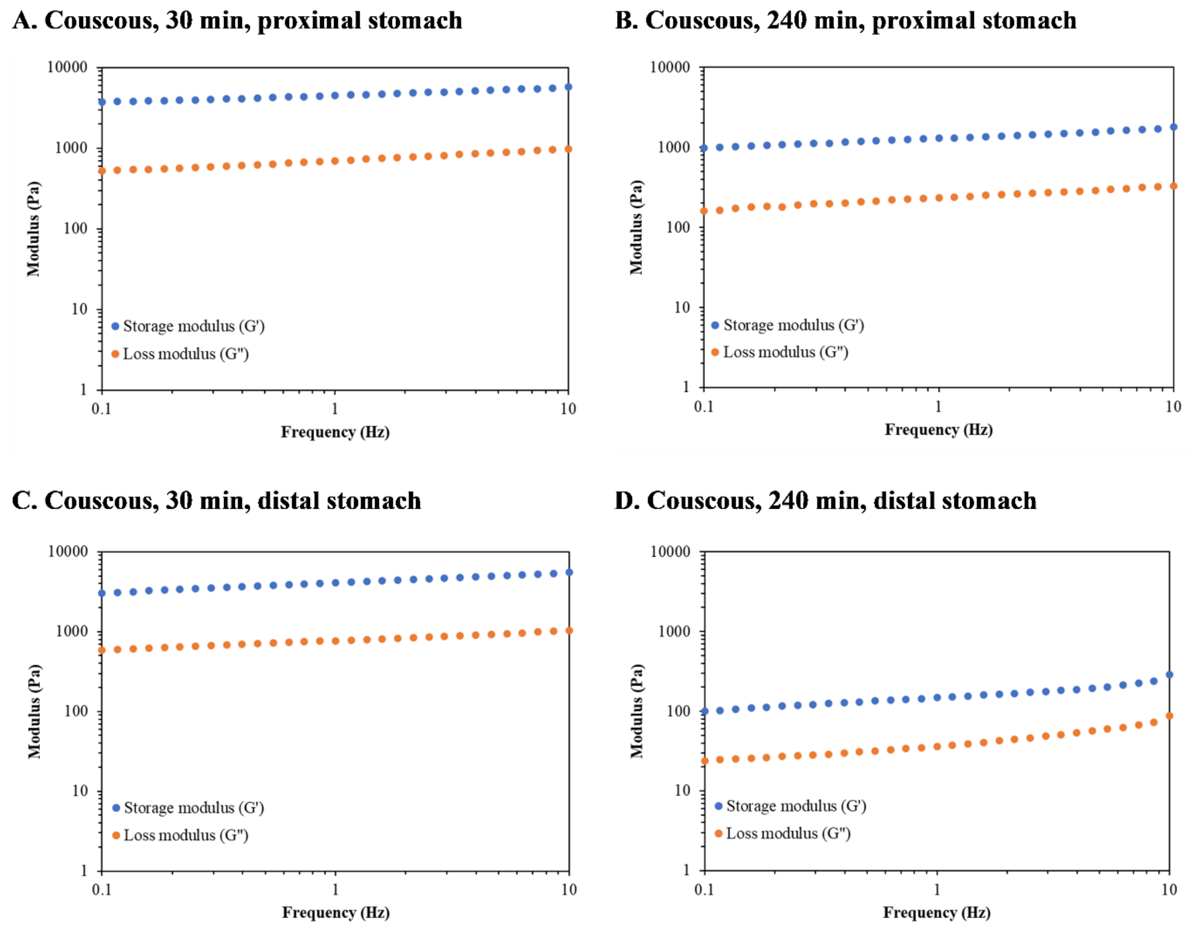
Supplemental Figure 1 Examples of binary images of gastric digesta used for extraction of particle size parameters for the wheat-based diets before digestion and after 30 and 240 min gastric digestion. The scale bar represents 1 cm and is the same for all images.



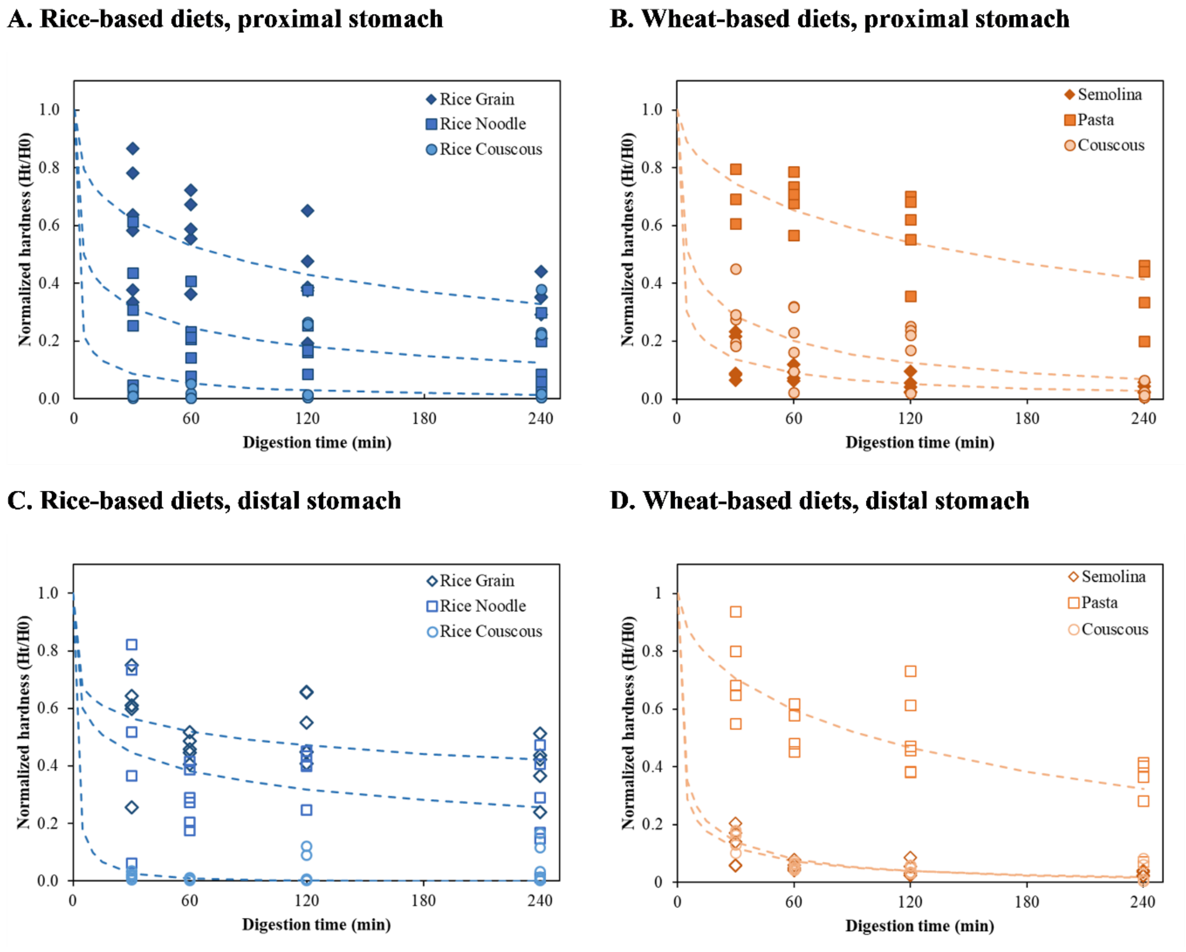
Supplemental Figure 2 Examples of binary images of gastric digesta used for extraction of particle size parameters for the rice-based diets before digestion and after 30 and 240 min gastric digestion. The scale bar represents 1 cm and is the same for all images.



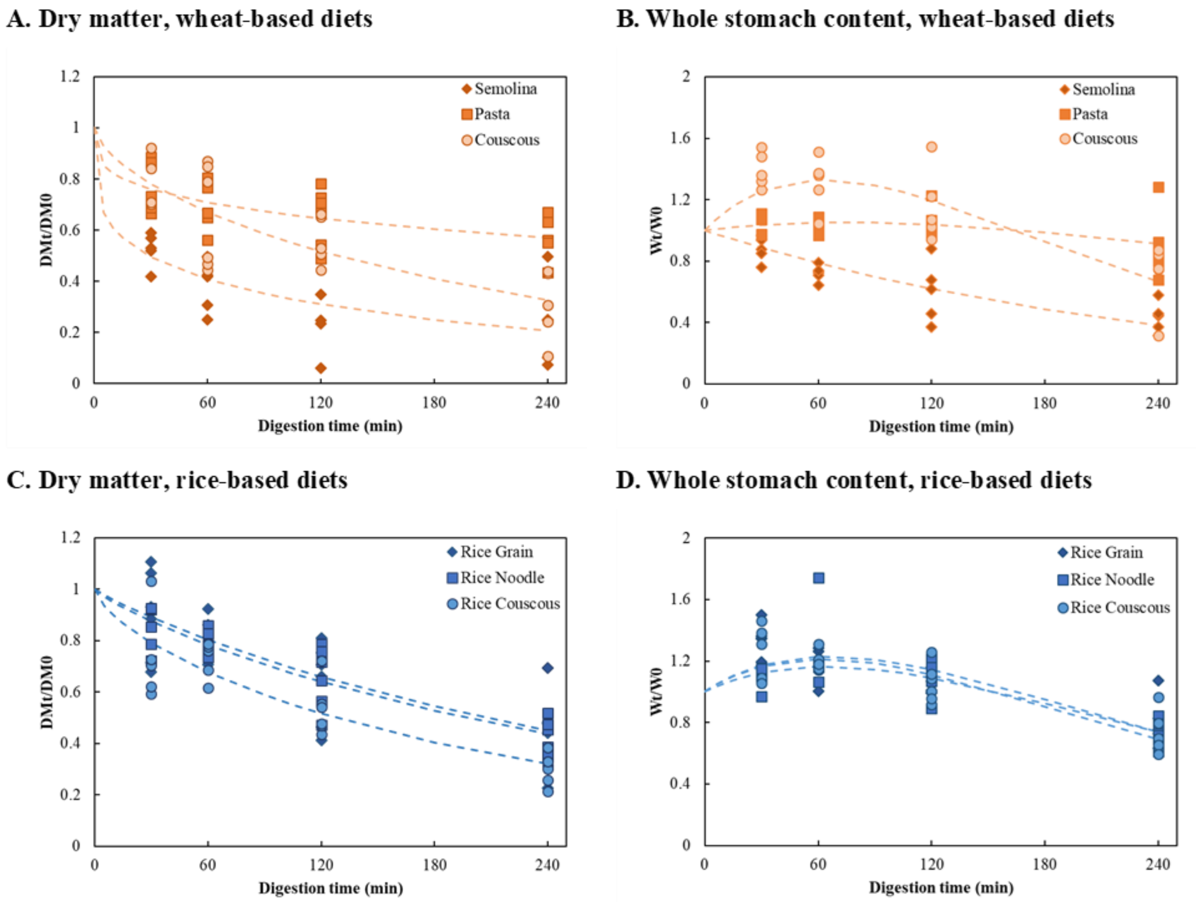
Supplemental Figure 3 Example of flow properties of couscous digesta from the proximal (A-B) and distal (C-D) regions of the stomach after 30 (A, C) and 240 (B, D) min gastric digestion.



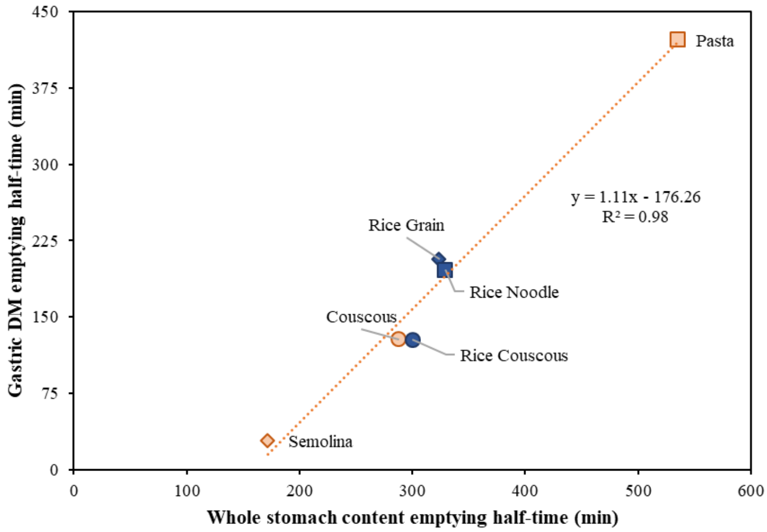
Supplemental Figure 4 Example of viscoelastic properties of couscous digesta from the proximal (A-B) and distal (C-D) regions of the stomach after 30 (A, C) and 240 (B, D) min gastric digestion.



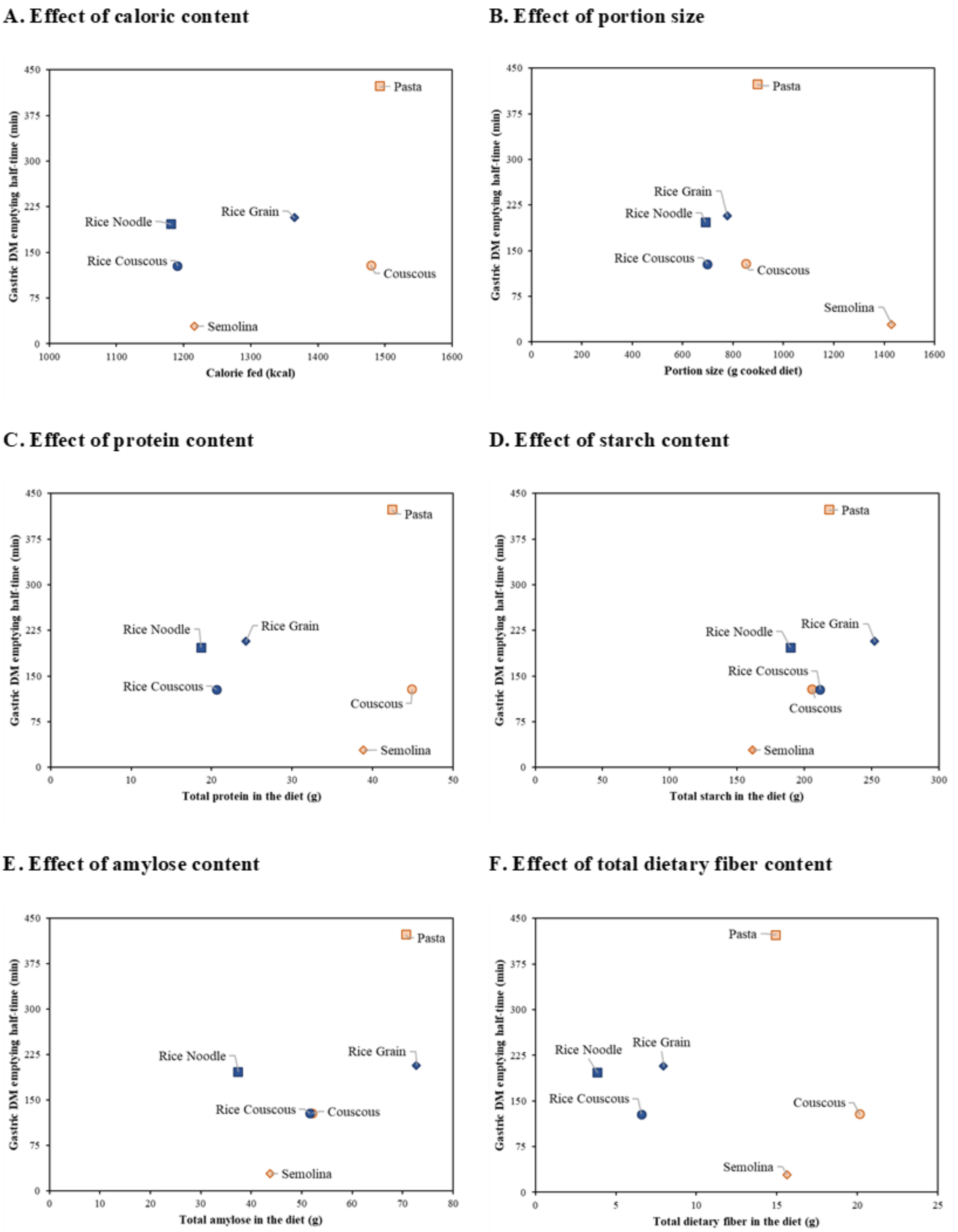
Supplemental Figure 5 Data spread of normalized hardness values of gastric digesta from (A-B) proximal and (C-D) distal stomach regions during 240 min digestion (total 252 data points). The predicted softening curves from average Weibull model parameters are represented as dashed lines. Rice- and wheat-based diets are represented as dark blue- and orange-colored data points and lines, respectively.



Supplemental Figure 6 Data spread of dry matter retention (A, C) and whole stomach content retention (B, D) during 240 min digestion (total 128 and 127 data points for dry matter retention and whole stomach content retention, respectively). The predicted softening curves from gastric emptying model parameters are represented by the dashed lines. Rice- and wheat-based diets are represented as blue- and orange-colored data points and lines, respectively.



Supplemental Figure 7 Relationship between gastric dry matter emptying half- time ($t_{1/2,\text{DM GE}}$) and whole stomach content emptying half- time ($t_{1/2,\text{whole GE}}$).



Supplemental Figure 8 Relationships between dry matter emptying half- time with (A) total caloric content, (B) portion size, (C) total protein content, (D) total starch content, (E) total amylose content, and (F) total dietary fiber content of the diets.