Rheological properties and effects of in vitro gastrointestinal digestion on functional components and antioxidant activities of cooked yam flour

Rui Zhou^{1,2} · Yoon-Han Kang^{2,3}

Received: 15 June 2018 / Revised: 12 December 2018 / Accepted: 14 December 2018 / Published online: 2 January 2019
© The Korean Society of Food Science and Technology 2019

Abstract There is dearth of documented information on rheological behavior, bioaccessibility and antioxidant potential of cooked yam flour (CY). This study was carried out to evaluate rheological properties and effects of in vitro gastrointestinal digestion (GID) on functional compositions and antioxidant activities of CY. CY displayed enhanced pseudoplastic and “gel-like” characteristics with incremental concentration (4.5–9.0%). After GID, contents of total polyphenols, flavonoids, sugar (TS), acidic polysaccharides (AP) and free amino acids (FAAs) significantly increased with maximal increment of 3.51-fold for TS followed by AP (3.05-fold), and DPPH, ABTS, FRAP and FIC assays pointed to a significant increase in antioxidant activity. Sixteen FAAs including 7 essential amino acids were detected with highest content of 9.81 mg/g for arginine. Large block remnants with a micro-porous structure were confirmed by scanning electron microscopy. Results indicate that CY with favourable swallowing performance can serve as a reliable source of bioaccessible and bioactive compounds with antioxidation.

Keywords Yam flour · Rheological property · Antioxidant · In vitro gastrointestinal digestion · Bioactive component

Introduction

Yam (*Dioscorea*, spp.) is widely cultivated in subtropical and tropical regions, and is a staple food in Southeastern Asia and Africa (Hsu et al., 2003). Nutritionally, yam tubers are excellent sources of starch, non-starch polysaccharide, glucoprotein, dietary fiber, minerals and other active phytochemicals, such as phenolic acids, allantoin and dioscin (Wu et al., 2016). It has also been used in traditional Chinese medicine for thousands of years because of health benefits that include anti-diarrheal, immunomodulatory, hypolipidemic, antidiabetic, and in vivo (animal) and in vitro antioxidant and anti-inflammatory properties (Adepoju et al., 2018; Dey et al., 2016; Son et al., 2014).

Starch is the predominant fraction of yams, accounting for 60.7–80.6% of the total biomass, followed by protein (6.3–12.2%) (Wu et al., 2016). An in vitro comparison of the digestion of the starch from raw yams, commercial maize, wheat, and sweet potato found higher resistant starch contents and better anti-digestion performance with potential anti-constipation and hypolipidemic effects in raw yams (Huang et al., 2016). Seven phenolic compounds (ferulic acid, sinapic acid, vanillic acid, caffeic acid, p-coumaric acid, quercetin dehydrate and kaempferol) in purple yam extracts were identified using high-performance liquid chromatography combined with high-resolution electrospray ionization mass spectrometry (Zhang et al., 2018), and Dey et al. (2016) discovered strong correlations between antioxidant and immunomodulatory

✉ Yoon-Han Kang
yhkang@gwnu.ac.kr

¹ College of Food Science and Technology, Hubei University of Arts and Science, Xiangyang, Hubei 441053, China

² Department of Food Science, Gangneung-Wonju National University, Gangneung, Gangwon 25457, Korea

³ Department of Food Processing and Distribution, Gangneung-Wonju National University, Gangneung, Gangwon 25457, Korea

activities, and the high amounts of phenolic acids and flavonoids in yams. The structural characteristics, rheological properties, physiological effects including antioxidant, antidiabetic and antitumor activities, as well as immune stability of yam polysaccharides during in vitro digestion have also been reported (Hao and Zhao, 2016; Ma et al., 2017). Additionally, macronutrients, energy content with significant reduction in all anti-nutrients, and phytochemical compositions with bioactivities of yam products have been significantly improved by food processing techniques, such as boiling, roasting and frying (Adepoju et al., 2018; Chen et al., 2017).

However, despite the fact that these functional components in raw and processed yams have shown important nutritional and biological properties including strong antioxidant activity, the real factors for healthy improvements are the contents and bioactivities of functional compounds after body digestion (He et al., 2017; Pellegrini et al., 2017). The in vivo health outcomes of the components of yams following their cooking preparation, consumption, and digestion are unknown. Among different methods evaluating the bioaccessibility of bioactive compounds, in vitro simulated gastrointestinal digestion is considered a valid, reproducible, simple, no ethical restrictions, cheap and rapid alternative of in vivo trials (e.g. animals and human studies) for screening food ingredients (Minekus et al., 2014). The in vitro model has been successfully applied to assess the release, digestibility and bioavailability of functional nutrients from multifarious food matrices including fruits, vegetables and cereal (Chandrasekara and Shahidi, 2012; He et al., 2017; Pellegrini et al., 2017). Moreover, yam foods are traditionally consumed in forms of liquid or semi-solid, so desirable rheological properties could contribute to industrial processing, pipeline transportation, and safe swallowing, especially for patients with dysphagia (Hadde and Chen, 2019). However, no studies have systematically reported the rheological characteristics, digestibility, and bioaccessibility of cooked yam flour.

Therefore, the aim of this work was to determine the contents of released functional components, antioxidant capacities, and microstructure of the matrixes during simulated in vitro gastrointestinal digestion, as well as steady and dynamic shear rheological behaviors of cooked yam flour. This study would provide baseline data on the bioaccessibility of nutritious compounds and antioxidant potential in dietary yam products for healthy benefits.

Materials and methods

Materials

Fresh yam tubers (*Dioscorea alata*) with the mean weight of 423.4 ± 28.2 g, length of 21.6 ± 2.1 cm, max-diameter of 9.4 ± 1.1 cm and min-diameter of 1.5 ± 0.1 cm ($n = 30$), originating from Andong, Gyeongsangbuk-do, Korea, were purchased from the North Andong National Agricultural Cooperative Federation. Yam starch with an amylose content of $31.23 \pm 0.57\%$ was isolated as we previously described (Zhou et al., 2017). Dried yam flours were prepared by using the method of Chen et al. (2017) with slight modifications. The yam tubers were washed, peeled, cut into slices (3 mm thickness), and then dried at 60°C for 48 h in a drying oven. The dried preparations were ground into flours and sieved through a 60-mesh screen. The flour samples with the color values of $L^* = 94.20 \pm 0.12$, $a^* = 0.26 \pm 0.01$, $b^* = 8.54 \pm 0.21$, and $\Delta E = 7.65 \pm 0.17$ determined using a model CR-400 Chroma Meter (Konica Minolta, Tokyo, Japan), were sealed in polyethylene bags and stored in a freezer (-20°C) until further analysis. The yield of the yam flours was $14.13 \pm 0.56\%$ of fresh weight. The flours had a moisture content of $10.36 \pm 0.21\%$ determined by a standard method (AACC, 2010) and total starch content of $68.89 \pm 2.07\%$ determined as previously described (Jiang et al., 2010).

Gallic acid, L-ascorbic acid, 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid) diammonium salt (ABTS), Folin-Ciocalteu's reagent, 3-(2-Pyridyl)-5,6-diphenyl-1,2,4-triazine-*p,p'*-disulfonic acid monosodium salt hydrate (ferrozine), D-galacturonic acid, D-glucose anhydrous, naringin, ethylene diamine tetra acetic acid (EDTA), 2,4,6-tris-(2-pyridyl)-1,3,5-triazine (TPTZ), α -amylase (A3176, Type VI-B, ≥ 5 units/mg solid) from porcine pancreas, pepsin (P7000, ≥ 250 units/mg solid) from porcine gastric mucosa, bile salts (B8756), pancreatin (P7545, $8 \times \text{USP}$) from porcine pancreas, and amino acid reference standards (each of purity $> 98\%$) were purchased from the Sigma-Aldrich Company (St. Louis, MO, USA). All other analytical grade chemicals used in the experiments were purchased from Fisher Scientific (Pittsburgh, PA, USA).

Rheological properties

Yam flour was mixed with distilled water to obtain a concentration ranging from 4.5 – 9.0% (w/w). Each suspension was allowed to evenly disperse and thoroughly hydrate by vortex mixing for 1 min followed by constant stirring at 600 rpm on a model SP131320-33Q Cimarec

ceramic stirring hot plate (Thermo Fisher Scientific, Waltham, MA, USA) for 30 min at room temperature. Each mixture was then heated in a boiling water bath for 20 min with stirring to allow complete gelatinization. After heating, the hot pastes were immediately transferred to a cold-water bath (4 °C) for 5 min, and subsequently used for rheological measurements. All samples were prepared in a closed system using a vial with a deep-skirted screw cap (Zhou et al., 2017).

Steady flow behavior

The flow rheological properties of the CY pastes were studied using a model AR 2000 rheometer (TA Instruments Inc., New Castle, DE, USA), equipped with a cone and geometry plate (40-mm diameter with a gap of 0.053 mm and an angle of 2°) (Zhou et al., 2017). During the experiment, the edge of the gap was covered with a thin layer of light paraffin oil to minimize evaporation. Steady shear experiments were performed with the shear rate increasing from 1 to 200 s⁻¹ at 25 °C, and the power-law model was used to fit the experimental flow curves with the following formula:

$$\eta_s = K \times \gamma^{n-1} \quad (1)$$

where η_s is the apparent viscosity (Pa s), γ is the shear rate (s⁻¹), K is the consistency index (Pa sⁿ), and n is the flow-behavior index. The apparent viscosity ($\eta_{a,100}$) at 100 s⁻¹ was calculated from the magnitudes of K and n .

Dynamic viscoelasticity (DV)

The DV of the CY pastes was measured with a rheometer using a parallel plate system (40-mm diameter with a 1 mm gap) (Zhou et al., 2017). Frequency sweep tests over the range of 0.1–10 Hz were performed at a constant strain of 2% and 25 °C. The 2% strain was within the linear viscoelastic region for all samples determined beforehand through a strain-sweep measurement at 1 Hz and 25 °C. The storage modulus (G'), loss modulus (G'') and complex-modulus ($G^* = [(G')^2 + (G'')^2]^{1/2}$) values as a function of frequency were obtained to characterize the mechanical spectra. The power-law correlation constants between G' and G'' versus ω for CY pastes were determined using the following two formulas (Razavi et al., 2016):

$$G' = k' \times \omega^{n'} \quad (2)$$

$$G'' = k'' \times \omega^{n''} \quad (3)$$

where k' (Pa s^{n'}) and k'' (Pa s^{n''}) are intercepts, n' and n'' are slopes of the frequency dependence of G' and G'' , respectively, and ω is the angular frequency (rad s⁻¹). The material stiffness parameter (A_α , Pa rad^{- α} s ^{α}) and order of

relaxation function (α) were calculated from a previously described method (Friedrich and Heymann, 1988):

$$G^* = A_\alpha \times \omega^\alpha \quad (4)$$

All samples were held on the plate for 3 min at the initial temperature to equilibrate the temperature and relax the pastes before rheological measurements were taken. All rheological measurements were taken in triplicate.

In vitro gastrointestinal digestion (GID)

Yam flour (0.5 g) was dispersed in 5 mL of distilled water, and each suspension was stirred continuously for 10 min before heating in a boiling water bath for 20 min. After cooling to 37 °C, the cooked samples were subjected to the GID test following the methods described by Minekus et al. (2014) with minor modifications. For oral digestion, each CY paste was mixed with 3.5 mL of 0.05 M phosphate buffer (pH 7.0), 0.5 mL of α -amylase solution (1 g of α -amylase dispersed in 10 mL distilled water followed by centrifugation at 3000×g for 10 min to obtain the supernatant), and 150 μ L of 50 mM CaCl₂. Each mixture was vortex mixed and shaken in a water bath at 100 rpm and 37 °C for 2 min. For gastric digestion, each mixture was then mixed with 5 mL of distilled water, 1 mL of 1% pepsin solution, and 30 μ L of 50 mM CaCl₂, and the pH was adjusted to 3 using 1 M HCl. Each mixture was incubated at 37 °C for 2 h in a shaking water bath (100 rpm). For intestinal digestion, the mixture was then added to 10 mL of 0.05 M phosphate buffer (pH 7.0), 3.0 mL of duodenal juice (12.5 g of bile salts and 2 g of pancreatin in 60 mL of 0.1 M NaHCO₃), and 240 μ L of 50 mM CaCl₂. The pH was adjusted to 7 using 1 M NaOH. Next, each mixture was shaken in the water bath at 100 rpm and 37 °C for 2 h, and boiled for 5 min before quickly cooling to room temperature. Subsequently, the CY pastes were immediately freeze-dried for microstructure examination by SEM. For determinations of functional components and antioxidant capacity determination, the digestive yam pastes were directly filtered through Whatman (No 2) filter paper, and the volume of each filtrate was adjusted to 50 mL with distilled water. After mixing well, each solution was stored at 4 °C until further use within 48 h.

In all cases, sample without the addition of three enzyme solutions was designated CY. The simulated orally-digested sample that included α -amylase in the absence of pepsin and duodenal juice was designated ODY. The simulated gastric-digested sample containing α -amylase and pepsin in the absence of duodenal juice was designated GODY. The simulated intestinally-digested sample created by the successive addition of α -amylase, pepsin, and duodenal juice was designated IGODY. During digestion, the

unused enzyme solution was replaced with the same volume of distilled water for each digestion experiment. For eliminating the possible influence of adding enzymes, the corresponding control in the presence of enzymes and absence of yam flours were designed as references, and the final experimental data against references were recorded for functional components and antioxidant capacity analysis in this study.

Functional composition analysis

Total polyphenol content (TPC)

TPC was determined by the Folin–Ciocalteu method as previously described (Chen et al., 2017) with slight modifications. A sample measuring 0.25 mL was combined with 0.25 mL of Folin–Ciocalteu reagent (50%, v/v) and 2.0 mL of distilled water, and vortex mixed. After 5 min, the mixture was neutralized with 0.25 mL of 20% Na₂CO₃ (w/w) and mixed well by vortexing. After placing in a water bath at 37 °C for 30 min, the absorbance of the mixture was measured at 750 nm. Gallic acid was used as a reference standard, with the results expressed as mg of gallic acid equivalents (GAEs) per gram of yam flour (mg GAE/g).

Total flavonoid content (TFC)

TFC was determined as previously described (Abeysinghe et al., 2007) with slight modifications. Briefly, 0.2 mL of sample was mixed with 2 mL of 90% diethylene glycol and mixed by vortexing. Next, 0.2 mL of 1 N NaOH was added before incubation in a water bath at 37 °C for 30 min. After the incubation, the absorbance of the mixture was measured at 420 nm. Naringin was used as a reference standard, with the results expressed as mg of naringin equivalents (NEs) per gram of yam flour (mg NE/g).

Total sugar content (TSC)

TSC was determined by the previously described phenol–sulfuric acid method (Dubois et al., 1956) with slight modifications. Briefly, the yam sample (1 mL) was mixed with 0.5 mL of 5% (w/v) phenol solution and 2.5 mL of concentrated sulfuric acid. After vortex mixing and resting for 5 min, the mixture was heated in a boiling water bath for 15 min before cooling down to room temperature. The absorbance was recorded at 490 nm and glucose was selected as a standard solution. The total sugar content (%) was calculated as follows:

$$\text{Total sugar content (\%)} = P_1/P_2 \times 100\% \quad (5)$$

where P_1 is the weight of total sugar (g), and P_2 is the weight of the sample (g).

Acidic polysaccharide content (APC)

APC was determined by the previously described sulfuric acid–carbazole colorimetry method (Do et al., 1993). Yam sample (0.5 mL) was mixed with 0.25 mL of 0.1% (m/v) carbazole solution in ethanol and then vortexed for 1 min. Next, 3 mL of concentrated sulfuric acid was added and evenly dispersed by vortexing. After heating at 85 °C for 5 min, the mixture was quickly cooled to room temperature in an ice water bath and the absorbance was recorded at 525 nm. β -D-galacturonic acid was selected as standard, and the acidic polysaccharide content (%) was calculated as follows:

$$\text{Acidic polysaccharide content (\%)} = F_1/F_2 \times 100 \quad (6)$$

where F_1 is the weight of acidic polysaccharide (g), and F_2 is the weight of the sample (g).

Free amino acid composition

Free amino acid content (FAAC) was determined as previously described (Xia et al., 2017). Before FAAC analysis, the sample was centrifuged twice (4400×g, 4 °C) for 30 min each time. The collected supernatants were mixed with equal volumes of sulfosalicylic acid (10%) to precipitate protein and centrifuged for 15 min (10,500×g, 4 °C). Aliquots (20 μ L) of the supernatants were injected into an L-8900 automated amino acid analyzer (Hitachi, Tokyo, Japan). The results were expressed as mg/g yam flour.

Antioxidant activity

DPPH radical scavenging test

The 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity was determined as previously described (Brand-Williams et al., 1995). A 0.5-mL volume of the sample was mixed with 2 mL of DPPH solution (0.1 mM in methanol) in a test tube wrapped with aluminum foil, followed by vortexing and incubation in the dark for 15 min. The absorbance of the solution was measured at 517 nm against methanol. The absorbance of a control was also recorded at 517 nm against methanol as the blank. L-ascorbic acid was used as the reference standard and the results were expressed in mg ascorbic acid equivalents (AAEs) per gram of yam flour.

ABTS radical scavenging test

The ABTS [2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt] radical scavenging activity was determined as previously described (Re et al., 1999). The green-blue free ABTS radical cation ($\text{ABTS}^{\cdot+}$) was produced by the reaction between 5 mL of 14 mM ABTS solution and 5 mL of 4.9 mM potassium persulfate ($\text{K}_2\text{S}_2\text{O}_8$) solution, and stored at room temperature in the dark for 16 h. Before use, this solution was diluted with distilled water to an absorbance of 0.7 ± 0.02 at 734 nm. The sample (0.5 mL) was mixed with 2.5 mL of ABTS working solution, and the absorbance of the mixture was measured at 734 nm after 6 min of incubation in darkness at room temperature. The absorbance of a control was also recorded at 734 nm against distilled water as a blank. Standard calibration curves were constructed by plotting percentage inhibition against the concentration of L-ascorbic acid, and the results were expressed as mg ascorbic acid equivalents (AAEs)/g of yam flour.

Ferric reducing antioxidant power (FRAP)

FRAP was evaluated as previously described (Benzie and Strain, 1996). Briefly, the working FRAP reagent was prepared from 20 mM $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, 10 mM 2,4,6-tripyridyltriazine in 40 mM HCl, and 0.3 M sodium acetate buffer (pH 3.6) in a volume ratio of 1:1:10, respectively. FRAP reagent was prepared fresh daily and warmed in a water bath at 37 °C before use. Next, 0.4 mL of the diluted sample or sodium acetate buffer (blank) was added to 3 mL of the FRAP solution, and the absorbance was determined at 593 nm after incubation for 10 min at 37 °C. L-ascorbic acid was used as a reference standard, and the results were expressed as mg AAE/g of yam flour.

Ferrous ion (Fe^{2+})-chelating activity (FIC)

The Fe^{2+} chelating activity of the extract was measured as previously described (Marathe et al., 2011). The reaction mixture consisted 1.5 mL of extract, 1.14 mL of double distilled water, 1.1 mL of $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ (0.2 mM), and 0.16 mL of ferrozine (5 mM). Absorbance was measured at 562 nm after 10 min, with EDTA used as the reference standard. The results were expressed as μmol of EDTA equivalent/g yam flour.

Microstructure

Field-emission scanning electron microscopy (SEM) was done using a JSM-7500F microscope (JEOL, Ltd., Tokyo, Japan) to evaluate the microstructure of freeze-dried yam samples before and after digestion (Zhou et al., 2017). The

freeze-dried yam samples were individually attached on an SEM stub with double-sided sticky tape. Stubs and samples were sputter-coated with a thin layer of gold-palladium alloy in a vacuum, and the microstructure was examined and photographed. The accelerating voltage and magnification were 5 kV and 3000 $\times$, respectively.

Statistical analyses

All tests were carried out at least in triplicate. The results were expressed as mean $\pm$ SD. All statistical computations and one-way analysis of variance (ANOVA) were achieved using Statistical Analysis System software for Windows (version 9.2; SAS Institute, Cary, NC, USA). Duncan's multiple-range test was also applied to establish the significance of differences among the mean values, using a significance test level at 5%.

Results and discussion

Rheological properties of CY pastes

Steady shear rheological analysis

The results of apparent viscosity versus shear rate fit well to the power law model (Eq. 1) with high determination coefficients ($R^2 > 0.99$) (Table 1). The apparent viscosity of all samples decreased with increasing shear rate (data not shown), with typical shear-thinning behaviors and pseudoplastic fluid characteristics being evident. With incremental changes in yam concentration (4.5–9.0%, w/w), the pseudoplasticity of CY paste was significantly increased with the lowest flow behavior index (0.264) for 9% yam paste ($p < 0.05$), showing suitable swallowing performance (Hadde and Chen, 2019). Similar trends were observed in the consistency index (k) and apparent viscosity ($\eta_{a,100}$), which increased by 1.6–10.8 times and 1.3–8.3 times, respectively, suggesting the presence of higher molecular interactions in the multi-component yam systems.

Oscillatory rheological analysis

For all samples, both G' and G'' increased with increasing ω , and G' values were always greater than the values of G'' throughout the frequency range (data not shown), demonstrating a typical gel-like system with an associated network. The correlation coefficients ($R^2 = 0.96 - 0.99$) between G' or G'' and ω were high, and the frequency dependence of the modules rapidly declined with increasing yam concentration, as achieved by n' and n'' reduction in the range of 1.6–35.3% and 13.6–41.7%, respectively

Table 1 Regressed parameter values of the power law model for CY pastes with different concentration at 25 °C

CY concentration (%)	K (Pa s ⁿ)	n	R ²	η _{a,100} (Pa s)
4.5	3.227 ± 0.099 ^{d1}	0.312 ± 0.006 ^a	0.992	0.136 ± 0.004 ^d
6.0	8.517 ± 0.220 ^c	0.285 ± 0.008 ^b	0.998	0.316 ± 0.007 ^c
7.5	16.509 ± 0.321 ^b	0.273 ± 0.008 ^{bc}	0.995	0.581 ± 0.009 ^b
9.0	37.679 ± 1.750 ^a	0.264 ± 0.005 ^c	0.999	1.270 ± 0.020 ^a

CY, cooked yam flour; K, consistency index; n, flow behavior index; R², determination coefficient; η_{a,100}, apparent viscosity at 100 s⁻¹

¹Data are expressed as mean ± SD (n = 3). Mean ± SD values of flow rheological parameters within the same column for each sample followed by different lower case superscript letters (^{a-d}) for CY gels with different concentration are significantly different at *p* < 0.05 by Duncan's multiple range test

Table 2 Frequency dependence of *G'* and *G''* and the Friedrich–Heymann model parameters for CY pastes with different concentration at 25 °C

CY concentration (%)	k'	n'	R ²	k''	n''	R ²	A _α	α	R ²
4.5	9.83 ± 0.17 ^{d1}	0.22 ± 0.01 ^a	0.965	2.55 ± 0.07 ^d	0.40 ± 0.01 ^a	0.999	10.13 ± 0.11 ^d	0.24 ± 0.01 ^a	0.971
6.0	23.47 ± 1.08 ^c	0.21 ± 0.02 ^a	0.983	6.85 ± 0.14 ^c	0.35 ± 0.02 ^b	0.999	24.42 ± 1.13 ^c	0.23 ± 0.01 ^{ab}	0.986
7.5	57.21 ± 1.93 ^b	0.20 ± 0.01 ^a	0.996	16.09 ± 0.31 ^b	0.31 ± 0.01 ^c	0.999	59.36 ± 1.47 ^b	0.21 ± 0.01 ^b	0.996
9.0	171.26 ± 2.98 ^a	0.14 ± 0.01 ^b	0.996	32.33 ± 1.35 ^a	0.23 ± 0.02 ^d	0.999	174.22 ± 3.34 ^a	0.15 ± 0.01 ^c	0.997

CY, cooked yam flour; k' and k'', intercepts; n' and n'' are slopes of the frequency dependence of *G'* and *G''*; R², determination coefficient; A_α, material stiffness; α, order of relaxation function

¹Data are expressed as mean ± SD (n = 3). Mean ± SD values of oscillatory rheological parameters within the same column for each sample followed by different lower case superscript letters (^{a-d}) for CY gels with different concentration are significantly different at *p* < 0.05 by Duncan's multiple range test

(Table 2). In addition, the values of A_α and α were calculated using the Friedrich and Heymann (1988) model with high correlation (R² = 0.97–0.99). With increasing yam concentration, the value of A_α significantly increased, while α was sharply and significantly reduced (*p* < 0.05) with the largest A_α (174.22 Pa rad^{-α} s^α) and the least α (0.15) for 9% yam paste, displaying a stronger network, higher number of intermolecular interactions, and more pseudoplastic flow behavior. The findings above were favourable for the management of dysphagia while CY swallowing (Hadde and Chen, 2019).

Functional components analysis

TPC and TFC

In vitro simulated gastrointestinal digestion had a significantly augmented TPC and TFC in water extracts from CY (Table 3). The TPC and TFC of 1.74 mg GAE/g and 0.542 mg NE/g, respectively, represented an increment during digestion of 0.99–1.59 times and 9–13% (*p* < 0.05), respectively. This could reflect that bound phenolics with the macromolecules, especially starch and dietary fibers, were continuously liberated through hydrothermal treatment and the cell wall dissolution by the digestive

enzymes. The free phenolics might possibly be absorbed in the small intestine or could be fermented by the microflora and partially absorb to gut epithelial cells, serving to counteract the effect of pro-oxidants in the body (Quiros-Sauceda et al., 2014).

TSC and APC

TSC and APC for CY were 11.42 and 3.21 g/100 g, respectively (Table 3). Surprisingly, these values rapidly increased by 3.37–3.51 and 2.85–3.05 times after in vitro simulated digestion. This is because the amylase from oral and intestinal digestion processes hydrolyzes starch into maltose, glucose, and oligosaccharides, and because pepsin and trypsin from the gastrointestinal digestion process break down proteins into oligopeptides and amino acids. Because of these activities, phytochemicals and non-starchy polysaccharides would be released upon cell wall disruption (Whitaker et al., 2003). However, no significant difference in TSC for CY during three models of digestion was found, and the TSC appeared to reach an equilibrium state (Table 3). These phenomena might possibly be attributed to highly resistant starch contents, and/or suppression of amylase caused by the release of phenolics and non-starchy polysaccharide during digestion (He et al.,

Table 3 Contents of total polyphenols, total flavonoids, total sugar, acidic polysaccharides and free amino acids of water extracts from cooked yam flours before and after in vitro gastrointestinal digestion

Sample	TPC (mg GAE/g)	TFC (mg NE/g)	TSC (g/100 g)	APC (g/100 g)	EAAC (mg/g)	TAAC (mg/g)	EAAC/TAAC
CY	1.74 ± 0.06 ^{d1}	0.542 ± 0.003 ^c	11.42 ± 0.34 ^b	3.21 ± 0.07 ^d	4.06 ± 0.09 ^b	22.94 ± 0.65 ^b	0.177 ± 0.002 ^b
ODY	3.46 ± 0.09 ^c	0.590 ± 0.009 ^b	49.95 ± 1.79 ^a	12.35 ± 0.13 ^c	4.31 ± 0.07 ^b	23.64 ± 0.76 ^b	0.179 ± 0.003 ^b
GODY	3.91 ± 0.13 ^b	0.606 ± 0.004 ^a	51.21 ± 1.10 ^a	13.38 ± 0.15 ^a	4.50 ± 0.16 ^b	25.15 ± 1.03 ^b	0.182 ± 0.006 ^b
IGODY	4.51 ± 0.23 ^a	0.613 ± 0.007 ^a	51.49 ± 1.47 ^a	13.00 ± 0.11 ^b	8.12 ± 0.21 ^a	30.79 ± 1.71 ^a	0.264 ± 0.007 ^a

CY, cooked yam flour before digestion; ODY, cooked yam flour after in vitro oral digestion; GODY, cooked yam flour after in vitro oral and gastric digestion; IGODY, cooked yam flour after in vitro oral, gastric and intestinal digestion; TPC, total polyphenol content; TFC, total flavonoid content; TSC, total sugar content; APC, total acidic polysaccharide content; EAAC, essential amino acid content; TAAC, total amino acid content

¹Data are expressed as mean ± SD (n = 3). Mean ± SD values of functional components within the same column for each sample followed by different lower case superscript letters (^{a-d}) for cooked yam flours with different digestion are significantly different at $p < 0.05$ by Duncan's multiple range test

2017; Huang et al., 2016). Interestingly, a certain amount of insoluble residues, generally regarded as dietary fibers, were suspended in the digestive juice. These residues can weaken the propulsive and mixing effects generated by peristalsis, thus attenuating postprandial glucose and insulin responses, and also can be fermented to generate short-chain fatty acids (Singh et al., 2010), indicating some potential application of dietary CY in controlling hyperglycemia and obesity.

Free amino acids

Sixteen amino acids including seven essential amino acids (EAAs) were detected, and nonessential amino acids (NEAAs) dominated the protein content in CY sample

(Tables 3 and 4). Arginine (8.55 mg/g), followed by serine (5.33 mg/g) and alanine (2.14 mg/g), were present in relatively higher amounts compared with the other amino acids. Concerning EAAs, CY predominantly contained threonine (0.91 mg/g), valine (0.78 mg/g), and lysine (0.62 mg/g). After digestion, an increase in contents was observed for all EAAs, especially leucine, phenylalanine, and lysine, with increases of 0.1–3.0, 0.2–2.6, and 0.2–1.1 times, respectively. EAA and TAA contents and the ratio of EAA contents and TAA contents for CY were 4.06 mg/g, 22.94 mg/g, and 0.177, respectively, which represented marked increases of 6.11–100.08%, 3.04–34.21%, and 1.11–49.06%, respectively. The maximal values of 8.12 mg/g, 30.79 mg/g, and 0.264, respectively, were obtained for IGODY (Table 3), indicating that a more

Table 4 Free amino acid contents of water extracts from cooked yam flours before and after in vitro digestion

Sample	Essential amino acid (mg/g)								
	Thr	Val	Met	Ile	Leu	Phe	Lys		
CY	0.91 ± 0.02 ^{a1}	0.78 ± 0.02 ^b	0.21 ± 0.01 ^b	0.49 ± 0.03 ^b	0.49 ± 0.01 ^b	0.55 ± 0.02 ^c	0.62 ± 0.02 ^c		
ODY	0.92 ± 0.03 ^a	0.82 ± 0.04 ^b	0.19 ± 0.01 ^b	0.50 ± 0.02 ^b	0.54 ± 0.02 ^b	0.63 ± 0.03 ^{bc}	0.71 ± 0.04 ^{bc}		
GODY	0.96 ± 0.04 ^a	0.83 ± 0.03 ^b	0.15 ± 0.01 ^c	0.53 ± 0.03 ^b	0.59 ± 0.04 ^b	0.68 ± 0.03 ^b	0.76 ± 0.02 ^b		
IGODY	0.93 ± 0.03 ^a	0.96 ± 0.04 ^a	0.29 ± 0.02 ^a	0.72 ± 0.02 ^a	1.98 ± 0.08 ^a	1.97 ± 0.08 ^a	1.27 ± 0.09 ^a		
Sample	Non-essential amino acid (mg/g)								
	Ser	Ala	Cys	Tyr	His	Arg	Gly	Glu	Asp
CY	5.33 ± 0.16 ^a	2.14 ± 0.07 ^a	0.00 ± 0.00 ^d	0.22 ± 0.01 ^c	0.44 ± 0.02 ^b	8.55 ± 0.26 ^b	0.48 ± 0.02 ^a	0.83 ± 0.03 ^a	0.89 ± 0.03 ^a
ODY	5.50 ± 0.30 ^a	2.18 ± 0.11 ^a	0.08 ± 0.01 ^c	0.37 ± 0.03 ^b	0.45 ± 0.03 ^b	8.58 ± 0.30 ^b	0.49 ± 0.02 ^a	0.82 ± 0.04 ^a	0.86 ± 0.02 ^a
GODY	5.64 ± 0.25 ^a	2.34 ± 0.16 ^a	0.17 ± 0.02 ^b	0.40 ± 0.02 ^b	0.48 ± 0.02 ^b	9.45 ± 0.17 ^a	0.51 ± 0.02 ^a	0.80 ± 0.03 ^a	0.85 ± 0.04 ^{ab}
IGODY	5.75 ± 0.14 ^a	2.41 ± 0.10 ^a	0.58 ± 0.02 ^a	1.57 ± 0.10 ^a	0.61 ± 0.02 ^a	9.81 ± 0.15 ^a	0.41 ± 0.02 ^b	0.75 ± 0.04 ^a	0.76 ± 0.04 ^b

CY, cooked yam flour before digestion; ODY, cooked yam flour after in vitro oral digestion; GODY, cooked yam flour after in vitro oral and gastric digestion; IGODY, cooked yam flour after in vitro oral, gastric and intestinal digestion. Thr (Threonine), Val (Valine), Met (Methionine), Ile (Isoleucine), Leu (Leucine), Phe (Phenylalanine), Lys (Lysine), Ser (Serine), Ala (Alanine), Cys (Cysteine), Tyr (Tyrosine), His (Histidine), Arg (Arginine), Gly (Glycine), Glu (Glutamic acid), Asp (Aspartic acid)

¹Data are expressed as mean ± SD (n = 3). Mean ± SD values of free amino acid contents within the same column for each sample followed by different lower case superscript letters (^{a-d}) for cooked yam flours with different digestion are significantly different at $p < 0.05$ by Duncan's multiple range test

balanced amino acid composition was obtained by the simulated digestion. This might be ascribed to the pepsin-mediated degradation of proteins into oligopeptides by cleavage of the peptide bonds between hydrophobic and, preferably, aromatic amino acids (phenylalanine, tryptophan, and tyrosine, etc.), and the cleavage of the peptide bonds formed by lysine and arginine by pancreatin containing trypsin (Whitaker et al., 2003). Surprisingly, the highest arginine content (8.55–9.81 mg/g; Table 4) was observed in the free amino acids for all yam samples. Arginine is the immediate precursor of nitric oxide, and it can act as a secondary messenger and an intercellular messenger to regulate vasodilation. Arginine also functions in immunoregulation, anti-diabetes activity, healing of wounds, and seminal emission (Claybaugh et al., 2014).

Antioxidant activity

Free radical scavenging activity on DPPH[•] and ABTS^{•+}

Both DPPH and ABTS assays have a similar reaction mechanism involving an electron transfer or hydrogen atom donation (Prior et al., 2005). CY displayed the lowest DPPH[•] and ABTS^{•+} scavenging activities (0.78 and 11.77 mg AAE/g, respectively), which were significantly increased by 1.61–2.74 and 2.82–4.60 times, respectively, with the highest values (2.91 and 65.95 mg AAE/g, respectively) for IGODY during in vitro digestion ($p < 0.05$) (Table 5). The obtained results agree with the previous demonstration that in vitro gastrointestinal digestion greatly improved the antioxidant activities of six quinoa seeds using four spectrophotometric assays (Pellegrini et al., 2017).

FRAP

The FRAP assay is applied to measure the reduction of Fe^{3+} -TPTZ to the intensely blue colored ferrous (Fe^{2+}) complex by antioxidants in acidic media (Benzie and

Strain, 1996). As seen from Table 5, significant differences in FRAP (all $p < 0.05$) were observed among CY and digestive samples. The highest antioxidant activity was again recorded for IGODY (7.35 mg AAE/g) with the largest variation of 116% compared with that of CY. The increasing antioxidant activity results agree with those presented by He et al. (2017) who reported that among 22 commercial fruit juices, the contents of polyphenol and polysaccharide, and their antioxidant activity measured by FRAP assay significantly increased after GID, with the best FRAP value displaying a 1.56-fold change.

FIC

FIC is an important antioxidant mechanism that retards metal-catalyzed oxidation (Marathe et al., 2011). The Fe^{2+} chelating capacity of yam samples was determined by measuring the iron-ferrozine complex. CY exhibited a significant increase in FIC values with a 1.71–5.41-fold change after the simulated gastrointestinal digestion ($p < 0.05$), with the highest value being 83.63 μmol EDTA/g for IGODY (Table 5). These results were similar to those presented by Chandrasekara and Shahidi (2012), who reported that, among five millet varieties with peeling and cooking treatments, the chelating activity increased by up to 20-fold in simulated gastrointestinal digested samples.

Correlation between functional components with antioxidant activities

Pearson's correlations between the contents of functional components and antioxidant activities were studied (data not shown). A strong and positive correlation ($R^2 > 0.81$, $p < 0.01$) was found between TPC or TFC and the antioxidant activity obtained with DPPH, ABTS, and FRAP. The FRAP and FIC results were significantly consistent with TAAC ($R^2 > 0.83$, $p < 0.01$). Similar results were observed in the correlation coefficients ($R^2 > 0.79$,

Table 5 Antioxidant activity of water extracts from cooked yam flours before and after in vitro digestion

Sample	DPPH (mg AAE/g)	ABTS (mg AAE/g)	FRAP (mg AAE/g)	FIC (μmol EDTA/g)
CY	$0.78 \pm 0.02^{\text{c1}}$	$11.77 \pm 0.49^{\text{d}}$	$3.40 \pm 0.15^{\text{c}}$	$13.04 \pm 0.23^{\text{d}}$
ODY	$2.03 \pm 0.06^{\text{b}}$	$45.02 \pm 1.01^{\text{c}}$	$5.14 \pm 0.12^{\text{b}}$	$35.35 \pm 1.09^{\text{c}}$
GODY	$2.07 \pm 0.06^{\text{b}}$	$58.42 \pm 2.03^{\text{b}}$	$5.38 \pm 0.19^{\text{b}}$	$41.11 \pm 1.45^{\text{b}}$
IGODY	$2.91 \pm 0.04^{\text{a}}$	$65.95 \pm 2.07^{\text{a}}$	$7.35 \pm 0.28^{\text{a}}$	$83.63 \pm 3.34^{\text{a}}$

CY, cooked yam flour before digestion; ODY, cooked yam flour after in vitro oral digestion; GODY, cooked yam flour after in vitro oral and gastric digestion; IGODY, cooked yam flour after in vitro oral, gastric and intestinal digestion

¹Data are expressed as mean $\pm$ SD ($n = 3$). Mean $\pm$ SD values of antioxidant capacity within the same column for each sample followed by different lower case superscript letters (^{a–d}) for cooked yam flours with different digestion are significantly different at $p < 0.05$ by Duncan's multiple range test

Fig. 1 SEM images of the raw yam starch (A), raw yam flour (B), and cooked yam flours before (C) and after (D, E, F) in vitro gastrointestinal digestion. (D) Depicts cooked yam flour after in vitro oral digestion (ODY). (E) Depicts cooked yam flour after in vitro oral and gastric digestion (GODY). (F) Depicts means cooked yam flour after in vitro oral, gastric, and intestinal digestion (IGODY). Scale bar denotes 50 μm

$p < 0.01$) between TSC or APC and ABTS and DPPH, while the correlation results ($R^2 < 0.49$) of FIC showed a smaller dependence with TSC or APC. Moreover, significant correlations ($R^2 > 0.73$, $p < 0.01$) were also obtained in the DPPH, ABTS, FRAP, and FIC results. These high correlations could be ascribed to bioactive compounds released or formed during digestion. Brand-Williams et al. (1995) confirmed that phenolics with a second hydroxyl group in the ortho or para position had larger activity,

compared to the meta position. Elias et al. (2008) reported that the proton or hydrogen atom donation, and electron-dense side chain groups from amino acid residues contribute to the radical scavenging or quenching activity in foods. Moreover, conjugation with phenolic compounds or protein, and the chelating ability of uronic acid and sulfate group, as well as reductive hydroxyl group terminals, are responsible for the antioxidant activity of polysaccharides (Wang et al., 2016).

SEM

Representative SEM images of raw yam starch (YS), raw yam flour (YF), and CY before and after in vitro gastrointestinal digestion are presented in Fig. 1. YS granules presented a typical oval and spherical shape with a smooth appearance (Fig. 1A). Dust-like particles including protein and fibers adhering to the surface of YS granules were evident for YF (Fig. 1B). Comparatively, CY samples before digestion (Fig. 1C) displayed an absence of the YS granular shape, and instead displayed characteristic blocks and irregular structures with fissures, which could be ascribed to the swelling and gelatinization of starches during cooking, and subsequent retrogradation/reassociation behaviors in the period of cooling (Chen et al., 2017). Surprisingly, remarkable micro-structural changes were observed for CY samples after digestion (Fig. 1D, E, F). Small fragments, shrinkage, cranny and wrinkles were visibly evident, as well as amorphous voids on the blocks were detected in all the digested samples. More importantly, with the deepening of the digestion process, some large block remnants with a rough surface and micro-porous structure still remained in the digestive juice, indicating the decreasing solubility of CY residues during in vitro digestion. These morphological observations are coincided with those obtained in functional components measurements, in which a large number of bioactive compounds were released from yam matrixes although TSC pointed to no significant difference in the process of three stages of digestion (Table 3).

Acknowledgements This research was supported by grants from the open technology program of GWNU Leaders in Industry-university Cooperation (GWNU LINC+) of Ministry of Education of Korea.

Compliance with ethical standards

Conflict of interest The authors have declared no conflict of interest.

References

- AACC International. Method 44-15.02 (Moisture). In: Approved Methods of the American Association of Cereal Chemists. 11th ed. St. Paul, Minnesota. American Association of Cereal Chemists International, USA (2010)
- Abeyasinghe DC, Li X, Sun CD, Zhang WS, Zhou CH, Chen KS. Bioactive compounds and antioxidant capacities in different edible tissues of citrus fruit of four species. *Food Chem.* 104: 1338–1344 (2007)
- Adepoju OT, Boyejo O, Adeniji PO. Effects of processing methods on nutrient and antinutrient composition of yellow yam (*Dioscorea cayenensis*) products. *Food Chem.* 238: 160–165 (2018)
- Benzie IFF, Strain JJ. The ferric reducing ability of plasma (FRAP) as a measure of “antioxidant power”: the FRAP assay. *Anal. Biochem.* 239: 70–76 (1996)
- Brand-Williams W, Cuvelier ME, Berset C. Use of a free radical method to evaluate antioxidant activity. *Lebensm. Wiss. Technol.* 28: 25–30 (1995)
- Chandrasekara A, Shahidi F. Bioaccessibility and antioxidant potential of millet grain phenolics as affected by simulated in vitro digestion and microbial fermentation. *J. Funct. Foods* 4: 226–237 (2012)
- Chen X, Lu J, Li X, Wang Y, Miao J, Mao X, Zhao C, Gao W. Effect of blanching and drying temperatures on starch-related physicochemical properties, bioactive components and antioxidant activities of yam flours. *LWT Food Sci. Technol.* 82: 303–310 (2017)
- Claybaugh T, Decker S, McCall K, Slyvka Y, Steimle J, Wood A, Schaefer M, Thuma J, Inman S. L-arginine supplementation in type II diabetic rats preserves renal function and improves insulin sensitivity by altering the nitric oxide pathway. *Int. J. Endocrinol.* 2014: 171546 (2014)
- Dey P, Ray S, Chaudhuri TK. Immunomodulatory activities and phytochemical characterisation of the methanolic extract of *Dioscorea alata* aerial tuber. *J. Funct. Foods* 23: 315–328 (2016)
- Do JH, Lee HO, Lee SK, Jang JK, Lee SD, Sung HS. Colorimetric determination of acidic polysaccharide from *Panax ginseng*, its extraction condition and stability. *J. Ginseng Res.* 17: 139–144 (1993)
- Dubois M, Gilles KA, Hamilton JK, Rebers PA, Smith F. Colorimetric method for determination of sugars and related substances. *Anal. Chem.* 28: 350–356 (1956)
- Elias RJ, Kellerby SS, Decker EA. Antioxidant activity of proteins and peptides. *Crit. Rev. Food Sci. Nutr.* 48: 430–441 (2008)
- Friedrich CHR, Heymann L. Extension of a model for crosslinking polymer at the gel point. *J. Rheol.* 32: 235–241 (1988)
- Hadde EK, Chen J. Shear and extensional rheological characterization of thickened fluid for dysphagia management. *J. Food Eng.* 245: 18–23 (2019)
- Hao LX, Zhao XH. Immune activities of the water-soluble yam (*Dioscorea opposita* Thunb) polysaccharides as affected by thermal, acidic and enzymatic treatments. *CYTA-J. Food* 14: 266–270 (2016)
- He M, Zeng J, Zhai L, Liu Y, Wu H, Zhang R, Li Z, Xia E. Effect of in vitro simulated gastrointestinal digestion on polyphenol and polysaccharide content and their biological activities among 22 fruit juices. *Food Res. Int.* 102: 156–162 (2017)
- Hsu CL, Chen W, Weng YM, Tseng CY. Chemical composition, physical properties, and antioxidant activities of yam flours as affected by different drying methods. *Food Chem.* 83: 85–92 (2003)
- Huang H, Jiang Q, Chen Y, Li X, Mao X, Chen X, Huang L, Gao W. Preparation, physico-chemical characterization and biological activities of two modified starches from yam (*Dioscorea opposita* Thunb.). *Food Hydrocoll.* 55: 244–253 (2016)
- Jiang H, Jane J, Acevedo D, Green A, Shinn G, Schrenker D, Srichuwong S, Campbell M, Wu Y. Variations in starch physicochemical properties from a generation-means analysis study using amylomaize V and VII parents. *J. Agric. Food Chem.* 58: 5633–5639 (2010)
- Ma F, Zhang Y, Liu N, Zhang J, Tan G, Kannan B, Liu X, Bell AE. Rheological properties of polysaccharides from *Dioscorea opposita* Thunb. *Food Chem.* 227: 64–72 (2017)
- Marathe SA, Rajalakshmi V, Jamdar SN, Sharma A. Comparative study on antioxidant activity of different varieties of commonly consumed legumes in India. *Food Chem. Toxicol.* 49: 2005–2012 (2011)
- Minekus M, Alminger M, Alvito P, Ballance S, Bohn T, Bourlieu C, Carrière F, Boutrou R, Corredig M, Dupont D, Dufour C, Egger L, Golding M, Karakaya S, Kirkhus B, Le Feunteun

- S, Lesmes U, Macierzanka A, Mackie A, Marze S, McClements DJ, Ménard O, Recio I, Santos CN, Singh RP, Vegarud GE, Wickham MS, Weitschies W, Brodkorb A. A standardised static in vitro digestion method suitable for food: an international consensus. *Food Funct.* 5: 1113–1124 (2014)
- Pellegrini M, Lucas-Gonzalez R, Fernández-López J, Ricci A, Pérez-Álvarez JA, Sterzo CL, Viuda-Martos M. Bioaccessibility of polyphenolic compounds of six quinoa seeds during in vitro gastrointestinal digestion. *J. Funct. Foods* 38: 77–88 (2017)
- Prior RL, Wu X, Schaich K. Standardized methods for the determination of antioxidant capacity and phenolics in foods and dietary supplements. *J. Agric. Food Chem.* 53: 4290–4302 (2005)
- Quirós-Sauceda AE, Palafox-Carlos H, Sáyago-Ayerdi SG, Ayala-Zavala JF, Bello-Perez LA, Alvarez-Parrilla E, de la Rosa LA, González-Córdova AF, González-Aguilar GA. Dietary fiber and phenolic compounds as functional ingredients: interaction and possible effect after ingestion. *Food Funct.* 5: 1063–1072 (2014)
- Razavi SMA, Alghooneh A, Behrouzian F, Cui SW. Investigation of the interaction between sage seed gum and guar gum: steady and dynamic shear rheology. *Food Hydrocoll.* 60: 67–76 (2016)
- Re R, Pellegrini N, Proteggente A, Pannala A, Yang M, Rice-Evans C. Antioxidant activity applying an improved ABTS radical cation decolorization assay. *Free Radic. Biol. Med.* 26: 1231–1237 (1999)
- Singh J, Dartois A, Kaur L. Starch digestibility in food matrix: a review. *Trends Food Sci. Technol.* 21: 168–180 (2010)
- Son IS, Lee JS, Lee JY, Kwon CS (2014) Antioxidant and anti-inflammatory effects of yam (*Dioscorea batatas* Decne.) on azoxymethane-induced colonic aberrant crypt foci in F344 rats. *Prev. Nutr. Food Sci.* 19: 82–88 (2014)
- Wang J, Hu S, Nie SP, Yu Q, Xie M. Reviews on mechanisms of in vitro antioxidant activity of polysaccharides. *Oxid. Med. Cell. Longev.* 64: 1–13 (2016)
- Whitaker JR. Proteolytic enzymes. In: *Handbook of Food Enzymology*. Whitaker JR, Voragen AGJ, Wong DWS (eds.) Marcel Dekker, Inc., New York, NY, USA pp. 993–1009 (2003)
- Wu ZG, Jiang W, Nitin M, Bao XQ, Chen SL, Tao ZM. Characterizing diversity based on nutritional and bioactive compositions of yam germplasm (*Dioscorea spp.*) commonly cultivated in China. *J. Food Drug Anal.* 24: 367–375 (2016)
- Xia Q, Wang L, Xu C, Mei J, Li Y. Effects of germination and high hydrostatic pressure processing on mineral elements, amino acids and antioxidants in vitro bioaccessibility, as well as starch digestibility in brown rice (*Oryza sativa* L.). *Food Chem.* 214: 533–542 (2017)
- Zhang J, Tian H, Zhan P, Du F, Zong A, Xu T. Isolation and identification of phenolic compounds in Chinese purple yam and evaluation of antioxidant activity. *LWT-Food Sci. Technol.* 96: 161–165 (2018)
- Zhou R, Bao H, Kang YH. Synergistic rheological behavior and morphology of yam starch and *Auricularia auricula-judae* polysaccharide-composite gels under processing conditions. *Food Sci. Biotechnol.* 26: 883–891 (2017)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.