African Journal of Science, Technology, Innovation and Development

ISSN: 2042-1338 (Print) 2042-1346 (Online) Journal homepage: http://www.tandfonline.com/loi/rajs20

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To cite this article: Yvonne Maphosa, Victoria A. Jideani & Oladayo Adeyi (2016): Effect of soluble dietary fibres from Bambara groundnut varieties on the stability of orange oil beverage emulsion, African Journal of Science, Technology, Innovation and Development, DOI: 10.1080/20421338.2016.1263436

To link to this article: http://dx.doi.org/10.1080/20421338.2016.1263436

Published online: 28 Dec 2016.

African Journal of Science, Technology, Innovation and Development, 2016
http://dx.doi.org/10.1080/20421338.2016.1263436

Effect of soluble dietary fibres from Bambara groundnut varieties on the stability of orange oil beverage emulsion

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Soluble dietary fibres (SDFs) [30% (w/w)] from four varieties of Bambara groundnut (BGN), viz. black-eye, brown-eye, brown and red were used to stabilize orange oil beverage emulsions at 6% (w/w) orange oil. Emulsion stability was studied using Turbiscan MA 2000 and in terms of oil-droplet size characterization. The volume-surface mean diameter ($d_{3,2}$) and equivalent volume-mean diameter ($d_{4,3}$) of the four emulsions ranged between 2.68–4.38 µm and 17.09–18.62 µm, respectively. Emulsions stabilized with black-eye-SDF and brown-SDF possessed the least and highest $d_{3,2}$ and $d_{4,3}$, respectively. The $d_{3,2}$ and $d_{4,3}$ of all four emulsions were significantly ($p < 0.05$) different. Emulsions were relatively stable to creaming and destabilized mainly by phenomenon involving oil-droplet aggregation. The backscattering flux of the emulsions ranged from 72.9% (brown-SDF stabilized emulsion) to 85.0% (black-eye-SDF stabilized emulsion). All four BGN SDFs greatly indicated their potential in stabilizing beverage emulsions.

Keywords: Bambara groundnut, emulsion, orange-oil, soluble dietary fibre, stability

Introduction

Beverage emulsions are defined as oil-in-water (O/W) emulsions that can be classified as flavour emulsions or as cloud emulsions (Reiner, Reineccius, and Peppard 2010; Gharibzahedi et al. 2012; Cheong et al. 2014). The instability of emulsions is a challenge, especially to beverage manufacturers, as beverages are expected to be stable, both as concentrates and as dilute, for a period of at least six months according to beverage standards (Yadav et al. 2007; Mirhosseini et al. 2008; Reiner, Reineccius, and Peppard 2010; Rezvani, Taherian, and Schleining 2011).

The instability of beverage emulsions can be attributed to the positive free energy present during the formation of dispersions (Gharibzahedi et al. 2012). This makes the whole system prone to separation through creaming, coalescence, flocculation and sedimentation (Mengual et al. 1999; Chanamai and McClements 2000). To increase the kinetic stability of beverages, approaches such as the inclusion of stabilizers, emulsifiers, and polysaccharides are adopted (Chanamai and McClements 2000; Rezvani, Taherian, and Schleining 2011; Cheong et al. 2014). Hydrocolloids and polysaccharides play a major role in stabilizing beverage emulsions (Dhingra et al. 2012; Acton 2012; Desplanques et al. 2012; Gharibzahedi et al. 2012). There is a growing interest in the food industry for new, natural emulsion stabilizers. Natural stabilizers are considered more biocompatible, affordable and available than synthetic ones, and are often non-toxic, while also possessing certain medicinal properties (Gabriel, Jideani, and Ikhu-Omoregbe (2013). Soluble dietary fibres from Bambara groundnut (BGN-SDF) have the potential as natural alternatives to synthetic stabilizer.

Various tests and instrumentation for characterizing the physicochemical characteristics of emulsions have been developed over the years (Gabriel, Jideani, and Ikhu-Omoregbe 2013). The Turbiscan is commonly employed in the prediction of future stability of emulsions (Adeyi 2014). Optical microscopy is also commonly employed to determine growth of emulsion droplets which is an indication of emulsion instability (Gabriel, Jideani, and Ikhu-Omoregbe 2013). From the microscopic images, information about droplet sizes and droplet size distribution can be obtained (Adeyi 2014). Diedericks (2014) concluded that the combination of 30% brown BGN-SDF and 6% oil gave the most stable emulsion However, nothing is reported about the stability of diluted BGN-SDF stabilized emulsions as well as the effect of black-eye, brown-eye and red BGN-SDFs on beverage emulsions. The aim of this study was to evaluate BGN-SDFs as potential orange oil beverage emulsion stabilizers with a view to provide the beverage industry with a low cost, alternative stabilizer.

Materials and methods

Materials

BGN seeds purchased from Triotrade (Johannesburg, South Africa) were sorted according to 'eye' colour into black-eye, brown-eye, brown and red varieties. Analytical grade chemicals were used in this study (Sigma-Aldrich, Johannesburg, South Africa). Cold pressed orange oil was purchased from Puris Natural Aroma Chemicals, South Africa.

Milling and wet fractionation of Bambara groundnut seeds

BGN seeds were washed, dried at 50°C for 48 h (Cabinet drier, Model: 1069616, Geiger and Klotzbucher, Cape Town, South Africa) and then milled (Hammer mill Bauermeister, Bauermeister Inc., Vernon Hills; sieve size: 250 µm). The method of Dalgetty and Baik (2003) was adopted in the wet fractionation of BGN flour. BGN flour (200 g) was mixed with 500 mL distilled water, blended for 3 min at the highest setting and the slurry was centrifuged (15 min, 25°C, 1500x *g*). The residue was used for the isolation of insoluble dietary fibre and the supernatant for the isolation of SDF.

Isolation of soluble dietary fibre

To isolate SDF, proteins were precipitated by adjusting the pH of the soluble fraction from pH 3 to 9 using 1 *N* NaOH and 1 *N* HCl (Dalgetty and Baik 2003). Following precipitation, the soluble fraction was centrifuged (10 min, 25°C, 1500 x *g*) and the sediment was collected as protein concentrate. The supernatant was subjected to a tangential flow filtration system (Spectrum Laboratories Inc., USA) and each fibre solution was washed with four diafiltration volumes to remove any contaminants. Waste was removed through a hollow fibre filtration outlet with a molecular weight cut off of 10 kD (Diedericks 2014). The recovered SDF was freeze-dried by placing 600 mL of each sample in trays that were loaded onto the freeze dryer shelf. The freeze-drying process was complete in 24 h.

Preparation of beverage emulsions

A formulation containing 30% (w/w) BGN-SDF, 6% (w/w) orange oil, 0.4% (w/w) citric acid, 0.1% (w/w) sodium benzoate, 0.1% (w/w) potassium sorbate and deionized water was used in the preparation of the orange oil beverage emulsion. Citric acid, sodium benzoate, potassium sorbate and deionized water (60°C) were mixed for 2 min at low speed by using a Waring blender. BGN SDF was then added to the mixture and blended for another 2 min at high speed. Orange oil was then added and blended at high speed for 2 min. The resultant emulsion was homogenized (5 min, 12000 rpm) using an Ultra Turrax homogenizer (IKA T25 digital, Janke and Kunkel, Staufen, Germany). The kinetic stability and microstructures of the emulsions were assessed immediately after homogenization.

Emulsion microstructure analysis

The microstructure of each freshly prepared emulsion was assessed using a digital microscope (Ken-a-Vision TU-19542C, Ken-a-Vision Mfg Co. Inc., USA) mounted with a digital camera. Each emulsion was diluted with deionized water at a ratio 1:3 (w/w), emulsion: water. A single drop of each emulsion was placed on a microscope slide, covered with a cover slip and observed at 100X magnification. Images were recorded using Applied Vision 4 software (Ken-a-Vision Mfg Co. Inc., version 4.1.12, USA).

Quantification of droplet sizes and droplet size distribution of emulsions by image analysis

Image processing and analysis of droplet size and droplet size distribution were carried out using software Image J v1.36b. The diameters of the oil droplet ($n = 100$) were measured individually in order to obtain a statistical estimate of the oil droplet diameters and oil droplet distribution in each sample according to the method of Tcholakova, Denkov, and Danner (2004). Droplet size distribution was generated by categorizing the classes belonging to a common interval and then analyzed using Microsoft™ Excel 2007 (Adeyi 2014). Oil droplet sizes were obtained in terms of volume-surface mean diameter ($d_{3,2}$) and equivalent volume-mean diameter ($d_{4,3}$) according to Equations 1 and 2, respectively.

$$d_{3,2} = \sum n_i d_i^3 \Big/ \sum n_i d_i^2 \qquad (1)$$

$$d_{4,3} = \sum n_i d_i^4 \Big/ \sum n_i d_i^3 \qquad (2)$$

where n_i is the number of droplets with diameter d_i.

Emulsion stability evaluation

The Turbiscan MA 2000 (Formulaction, Toulouse, France) was used in evaluating the stability of the four BGN-SDF stabilized beverage emulsions according to the method of Adeyi (2014). For each emulsion, a 7 mL sample was measured into a Turbiscan tube (65 mm length) and measured. The measurement involved scanning each sample along its height for 1 h at 10 min intervals. The backscattering (BS) and transmission curves generated were used to provide the BS and transmission flux percentage relative to the instrument's internal standard as a function of the height of the sample. Stability and instability of the emulsions were observed and analyzed by carrying out multiple scans.

Emulsion turbidity loss rate assessments

The turbidity of the four BGN SDF stabilized beverage emulsions were determined by diluting the beverage emulsions in a 10% sugar solution to 0.25% (w/w) and storing the diluted emulsions at room temperature in plastic bottles. Absorbance readings were then taken using a temperature controlled (20°C) UV-visible spectrophotometer (UV-1700 PharmsSpec, Shimadzu, Japan) at a wavelength of 500 nm using plastic cuvettes (Macro PS, Lasec, 10X10X45 mm). Measurements were followed as described by Gharibzahedi et al. (2012), and the turbidity loss rate determined as k by using the first-order model as shown in Equation 3.

$$\ln A = \ln A_0 - kt \qquad (3)$$

where: t is time, A is the absorbance at time t, A_0 is the absorbance at time 0 and k is the first-order rate constant.

Oil binding capacity of BGN fibres

The method described by Maphosa and Jideani (2016) was applied to determine the oil binding capacity (OBC) of the BGN SDFs. Canola (5 g) was mixed with 1 g SDF in a 50 mL centrifuge tube, vortexed (30 sec at 5 min intervals for 30 min), centrifuged (25 min, 23°C, 1600 x *g*,) and then the supernatant was decanted and weighed. OBC was expressed as grams of oil retained/grams of fibre.

Assessment of neutral sugars in BGN SDFs

Neutral sugars were analyzed in BGN SDFs according to the method of Maphosa and Jideani (2016). SDFs were hydrolyzed with 1M H_2SO_4 at 100°C for 90 min to yield monomers, then centrifuged (3000 x *g*, 15 min, 21°C) and filtered to remove any suspensions. Neutral sugars were then analyzed in the supernatants by spectrophotometry (340 nm) using K-Arga, K-Fucose, K-Mangl, K-Rhan, K-Uronic and K-Xylose assay kits (Megazyme International, Ireland).

Densities of BGN SDFs

The method of Parrott and Thrall (1978) was used to determine both bulk and direct densities. Bulk density was determined by adding 2 g of each BGN SDF into a graduated syringe and manually applying sufficient pressure while gentle tapping the syringe on a bench until the contents were packed tightly. Direct density was determined by carefully adding SDF to the 5 mL mark in a 10 mL graduated cylinder. The fibre was then emptied and weighed. Direct and bulk densities were expressed as g/mL.

Hysteresis loop areas and consistency of BGN SDF stabilized emulsions

Samples (25 mL) were carefully transferred into the rheometer cup (MCR 300 Paar Physical hybrid rheometer, Discovery HR-1) and allowed to equilibrate for 5 min. In order to describe the time dependent flow behaviour, experimental data (shear stress-shear rate) of forward and backward curves were fitted to Power law model (Equation 4). The hysteresis loop area (Equation 5) was calculated as the area between the upstream data and downstream data (Tarrega, Duran, and Castell 2004; Koocheki and Razavi 2009).

$$\tau = K\gamma^n \tag{4}$$

where: n = flow behaviour index, K = consistency efficiency, γ = shear rate, τ = shear stress.

$$\int_{\gamma_1}^{\gamma_2} K\gamma^n - \int_{\gamma_1}^{\gamma_2} K'\gamma^{n'} \tag{5}$$

where, K, K' are the consistency coefficients and n, n' are the flow behaviour indices for upward and downward measurements, respectively. Each experiment was performed in duplicate.

Data analysis

For data analysis, IBM Statistical Package for the Social Science (IBM SPSS, version 22) was used. The results were subjected to multivariate analysis of variance (MANOVA) to determine mean differences between treatments and Duncan's multiple range test was conducted to separate mean differences where differences exist. Results were expressed as mean ± standard deviation and as mean ± standard error for the turbidity loss rate model parameters. The goodness-of-fit of the models was assessed using the coefficient of determination (R^2).

Results and discussions

Effect of BGN SDFs on droplet size and droplet size distribution of orange oil beverage emulsion

The droplet size distribution (DSD) of the emulsions is shown in Figure 1. The DSD of the emulsion stabilized with black-eye SDF had the highest height and the smallest width. This indicated that black-eye SDF emulsion was characterized by the highest droplet volume (86%) and the smallest droplet size. The curves for brown and red SDF stabilized emulsions had the least heights (38% and 39%, respectively) and both had broader bases than the black-eye and brown-eye SDF stabilized emulsions curves (Figure 1). This indicated that these emulsions had larger oil droplets and the low droplet volume. Behrend, Ax, and Schubert (2000) explained that the addition of stabilizers to an emulsion reduces its droplet size. However, the stabilizing properties of the system determine the coalescence of droplets after disruption (homogenization) thereby determining the final droplet size distribution. Therefore, black-eye SDF stabilized emulsion could be deduced to have the highest strength and matrix to stabilize emulsions among BGN SDFs.

Brown and red SDF stabilized emulsions could be assumed to be the least stable amongst the four emulsions because larger droplet sizes in emulsion systems have a greater tendency of coalescence, having higher impact and magnitude during collision (Behrend, Ax, and Schubert 2000; Adeyi 2014). None of the distribution (Figure 1) showed a perfect bell shape and all tended to have a shoulder which could be an indication of the presence of a second population (Chanamai, Herrmann, and McClements 2000). This could mean that all the emulsions were poly-dispersed in nature (Kumar, Kumar, and Mahadevan 2012; Adeyi 2014). The graphs showed that all four BGN SDFs were capable of forming emulsions with orange oil.

Table 1 gives a comparison of the droplet sizes of the four emulsions in terms of volume-surface mean diameter

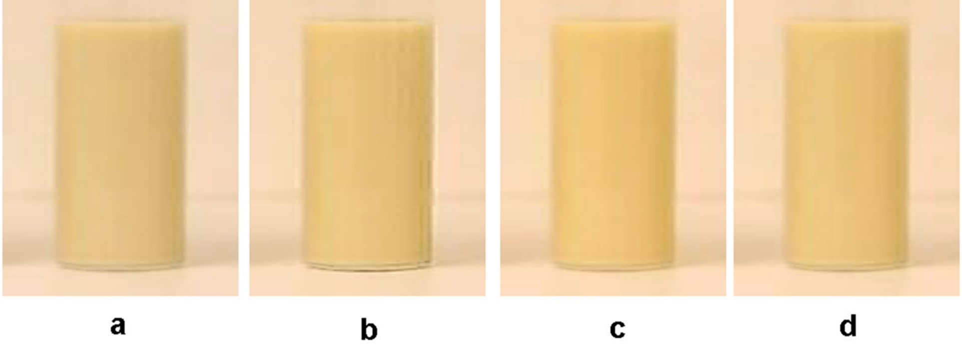

Figure 1: Droplet size of Bambara groundnut soluble dietary fibre stabilized emulsions.

Table 1: Effect of Bambara groundnut soluble dietary fibres on oil droplet size and backscattering.

Soluble fibre variety	$d_{3,2}$ (µm)	$d_{4,3}$ (µm)	Initial BS (%)
Black-eye	2.68 ± 0.48^a	4.38 ± 0.25^a	84.97 ± 0.27^a
Brown-eye	4.92 ± 0.59^b	5.72 ± 0.06^b	82.74 ± 0.45^b
Red	9.82 ± 0.11^c	11.08 ± 0.07^c	75.65 ± 0.02^c
Brown	17.09 ± 0.07^d	18.62 ± 0.11^d	72.90 ± 0.08^d

Values are mean ± standard deviation. Means within a column followed by the same superscript are not significantly [$p > 0.05$] different. $d_{3,2}$: volume-surface mean diameter. $d_{4,3}$: equivalent volume-mean diameter. BS: Backscattering.

($d_{3,2}$) and equivalent volume-mean diameter ($d_{4,3}$). $d_{3,2}$ gives information regarding the size of emulsion where most droplets fall while $d_{4,3}$ is a measure of changes in droplet size involving emulsion destabilization process. The $d_{3,2}$ of the four emulsions ranged between 2.68 and 17.09 µm while the $d_{4,3}$ ranged between 4.38 and 18.62 µm. The smallest and highest $d_{3,2}$ and $d_{4,3}$ were found in emulsions stabilized with black-eye and brown SDFs, respectively. The $d_{3,2}$ and $d_{4,3}$ of all four BGN SDF stabilized emulsions were significantly different ($p < 0.05$). A relatively smaller $d_{3,2}$ observed in brown SDF stabilized emulsion indicated the presence of larger droplet sizes. These observations were in agreement with the results reported in the previous section (Figure 1) where black-eye SDF stabilized emulsion was shown to have the smallest droplet sizes whereas brown showed the largest droplet sizes.

In terms of $d_{3,2}$ and $d_{4,3}$, black-eye SDF stabilized emulsion can be concluded to be the most stable emulsion because the physical stability of emulsions is largely dependent on droplet size (Behrend, Ax, and Schubert 2000; Chanamai, Herrmann, and McClements 2000; Mirhosseini et al. 2008; Dickinson 2008). Since all the emulsions were prepared with the same concentration of BGN SDF and orange oil, the differences in droplet sizes and droplet size distribution could be attributed to BGN varietal differences.

Effect of BGN soluble dietary fibres and orange oil on emulsion microstructure

The microstructures of freshly prepared emulsions stabilized with BGN SDFs are shown in Figure 2. The small droplets observed in the micrographs represent the dispersed phase (orange oil) and the empty spaces represent the continuous phase (BGN SDF dispersion). The strand-like clumps can be assumed to be BGN SDF within the system. Black-eye and brown-eye SDF stabilized emulsion (Figure 2(a) and (b)) showed very small oil droplets dispersed evenly throughout the system as well as smaller clumps of SDF. This could be an indication that black-eye and brown-eye SDFs have more emulsion forming strength. Brown and red SDF stabilized emulsions (Figure 2(c) and (d)) showed coalescence as small oil droplets adsorbed on the surface of larger ones as well as flocculation as groups of oil droplets clumped together (Adeyi 2014). Consequently, the oil droplets of the brown and red SDF stabilized emulsions would be expected to aggregate and thus destabilize at a faster rate than black-eye and brown-eye SDF stabilized emulsions over time, thus making them less stable (Mirhosseini et al. 2008).

Aveyard, Bink, and Clint (2002) reported that stabilizers cover the temporary interface, preventing oil droplets from coalescing, and therefore result in a lower $d_{3,2}$. From this study, it can be assumed that black-eye and brown-eye SDFs completely covered the temporary interface, and thereby gave rise to smaller droplets.

Storage stability of BGN fibre stabilized emulsions

The effect of BGN SDFs on the initial backscattering (BS) of emulsions is shown in Table 1. Backscattering gives an indication of the structure of the emulsion before destabilization; thus the highest percentage indicated initial high stability (Mengual et al. 1999). A higher BS percentage indicates that the emulsion consists of a higher population of oil droplets with small droplet sizes that disperse a higher amount of light (Adeyi 2014). The BS flux percentage of the four SDF stabilized emulsions ranged from 72.90% (brown) to 84.97% (black-eye). All four emulsions differed significantly ($p < 0.05$) in respect of BS flux percentage. Diedericks (2014) reported a lower BS value (62.99%) for brown BGN SDF stabilized emulsions. From Table 1, black-eye SDF stabilized emulsion could be deduced to be the most stable system, as it had the highest BS percentage meaning the emulsion had relatively smaller, evenly dispersed droplets (Adeyi 2014).

The Turbiscan profiles of the four emulsions are shown in Figure 3. The x-axis represents the height of the tube and the y-axis represents the BS flux percentage. The Turbiscan profiles are represented by the normal mode (above) and their respective reference mode (below). The scans of all four emulsions follow the same path as the

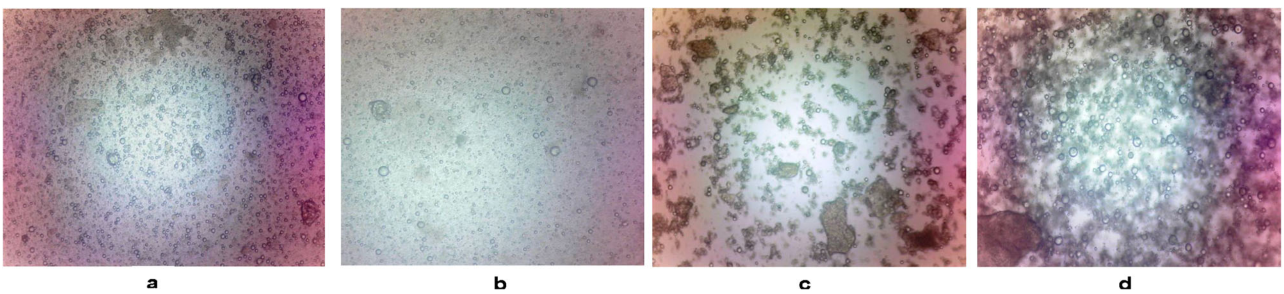

Figure 2: Photo micrographs of emulsion stabilized with Bambara groundnut soluble dietary fibre **a**) Black-eye **b**) Brown-eye **c**) Brown **d**) Red.

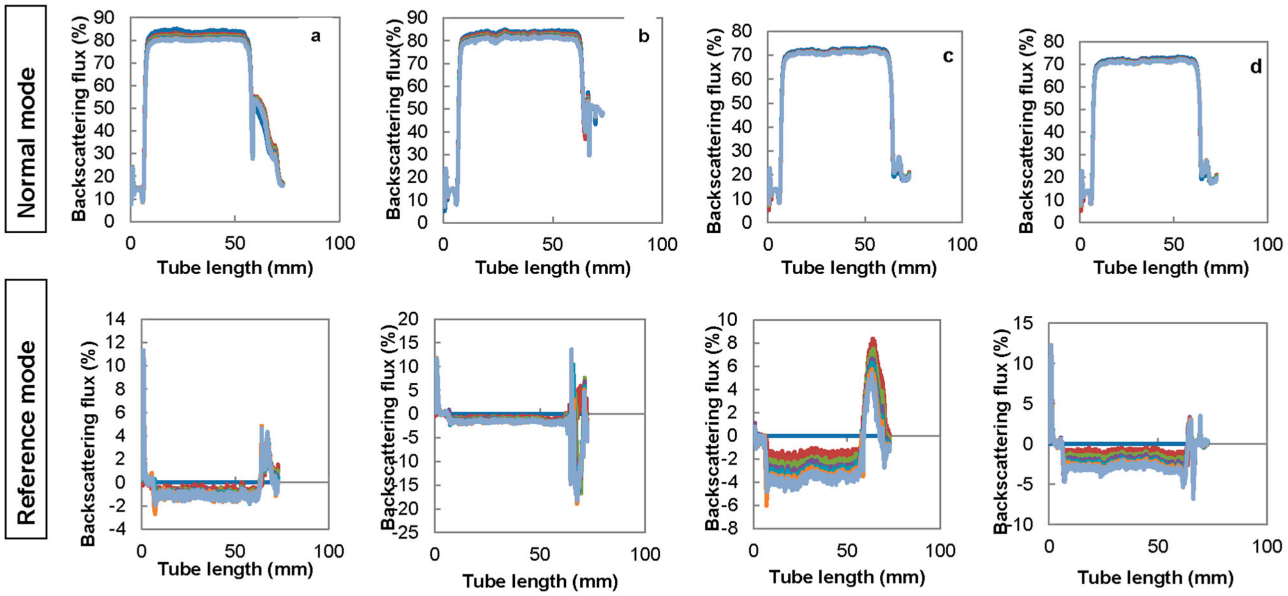

Figure 3: Changes in backscattering profile as a function of sample height during storage of emulsions stabilized by four varieties of Bambara groundnut soluble dietary fibre **a**) Black-eye **b**) Brown-eye **c**) Brown **d**) Red.

initial scan. However, the scans did not overlay perfectly, showing a decrease in BS flux percentage. This observation in all four emulsions indicated that the main phenomenon of disintegration in the emulsions was particle aggregation which could be attributed to either flocculation or coalescence. This is in agreement with Diedericks (2014) who reported that BGN SDF stabilized emulsions destabilized by flocculation.

The reference modes of red and brown SDF stabilized emulsions (Figure 3(c) and (d), respectively) showed more separation between the various scans compared to those of black-eye and brown-eye SDF stabilized emulsions (Figure 3(a) and (b), respectively), indicating that red and brown SDF stabilized emulsions were relatively less stable and showed higher destabilization due to droplet aggregation. These observations agreed with the microstructure and droplet size analyses (in the first two parts of the 'Results and discussion' section) which revealed that larger oil droplets were associated with brown and red SDF stabilized emulsions while smaller, more evenly dispersed oil droplets were associated with black-eye and brown-eye SDF stabilized emulsions. Reference modes were constructed relative to the normal scan and were used to show relative changes with time in all four emulsions.

Figure 4 shows the effect of BGN SDFs on the BS flux (%) kinetics, indicating how they compared to each other in terms of stability over time. To quantify the changes in particle size variation, such as coalescence and flocculation in the emulsions, the variation in BS in the 20–40 mm zone was monitored over 60 min for samples stored in inert condition at 20°C. The further the graphs were from the origin, the less stable the emulsion was; hence, graphs that were closer to zero at any given time were considered more stable. Black-eye SDF gave the most stable emulsion while brown SDF gave the least stable emulsion (Figure 4). These results agreed with those given in the previous sections where it was

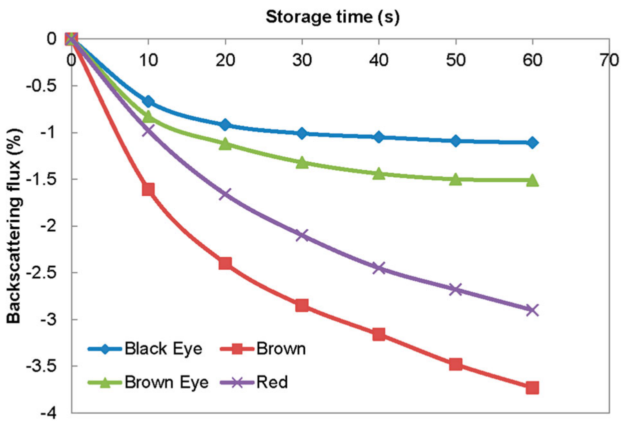

Figure 4: Variation in backscattering in the 20–40 mm zone for emulsions stabilized by different varieties of Bambara groundnut soluble dietary fibre.

established that black-eye SDF stabilized emulsion was the most stable emulsion while brown SDF stabilized emulsion was the least stable.

BGN SDFs acted as stabilizers in the emulsions systems. Stabilizers are defined by Behrend, Ax, and Schubert (2000) as non-surface active macromolecules which thicken the continuous phase thereby decreasing the mobility of oil droplets therefore preventing them from coalescing.

Turbidity loss rates of BGN soluble dietary fibre stabilized emulsions

The turbidity loss rates of BGN SDF stabilized emulsions were assessed under accelerated conditions so as to simulate their shelf lives in the finished products. Turbidity loss rate is a tool of assessing cloud stability of emulsions in diluted form (Mirhosseini et al. 2008). Table 2 shows the constrained non-linear regression parameters of the turbidity loss rate model. The absorbance (A) of the BGN SDF stabilized emulsions ranged from 0.181

Table 2: Turbidity loss rate model parameters.

Variety	k (day)	A	R^2
Black-eye	0.070 ± 0.00^a	0.211 ± 0.07^a	0.895
Brown-eye	0.084 ± 0.01^b	0.250 ± 0.01^b	0.862
Red	0.161 ± 0.01^c	0.242 ± 0.02^c	0.840
Brown	0.221 ± 0.01^d	0.181 ± 0.01^d	0.980

Values are mean ± standard error. Means within a column followed by the same superscript are not significantly [$p > 0.05$] different. A: absorbance. k: turbidity loss rate. R^2: coefficient of determination.

(brown SDF stabilized emulsion) to 0.250 (brown-eye SDF stabilized emulsion) and all differed significantly ($p < 0.05$). Black-eye SDF stabilized emulsion had the least ($p < 0.05$) turbidity loss rate (k) of 0.070/day and brown-eye SDF stabilized emulsion had the highest ($p <$ 0.05) turbidity loss rate (k) (0.221/day). The coefficient of determination (R^2) of all four BGN SDF stabilized emulsions was ≥ 0.084, indicating that the model could be successfully used in describing the turbidity loss rate parameters.

Figure 5 shows the plots of the logarithm (Ln) of absorbance as an indicator of turbidity loss rate for the four BGN SDF stabilized emulsions. All four BGN SDF stabilized emulsions showed a decrease in turbidity with storage as evidenced by the negative slopes on the graphs. A decrease in turbidity of emulsions during storage has been reported by other researchers (Mohaghe-ghi et al. 2011; Gharibzahedi et al. 2012). This decrease in turbidity can be attributed to loss of SDF around the layers of film formed at interfacial surface (Mohagheghi et al. 2011). Loss of turbidity could also have been due to factors such as flocculation, coalescence and aggregation which would have resulted in an increase in average droplet sizes which would consequently lead to destabilization of the emulsions (Mirhosseini et al. 2008; Mohagheghi et al. 2011; Homayoonfal, Khodaiyan, and Mousavi 2015). A lower amount of turbidity loss is an indication of higher stability and suggests that the emulsion in question would maintain its cloudiness for longer periods of time (Gharibzahedi et al. 2012). Such behaviour would attract more consumer acceptability in products such as soft drinks (Homayoonfal, Khodaiyan, and Mousavi 2015).

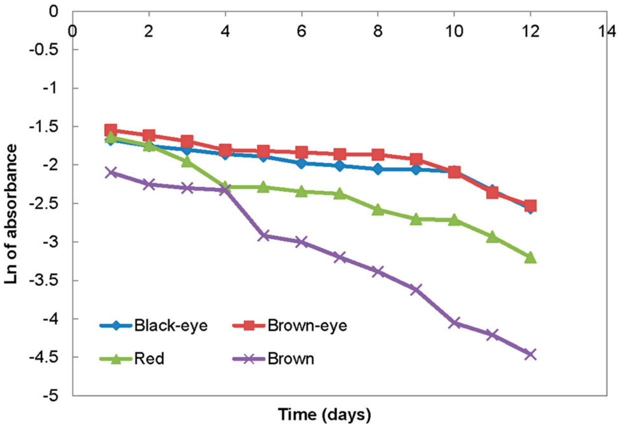

Figure 5: Turbidity loss of four Bambara groundnut soluble dietary fibre stabilized emulsions.

The results obtained in this study agreed with the results of the Turbiscan analysis discussed in the third part of the 'Results and discussion' section. Turbiscan analysis predicted that black-eye and brown-eye SDF stabilized emulsions would have the highest stability with time while brown SDF stabilized emulsion would have the least. Furthermore, the smaller $d_{3,2}$ of black-eye and brown-eye SDF stabilized emulsions could explain the turbidity loss rates of these emulsions because emulsion stability is largely dependent on droplet sizes with smaller droplets giving more stable emulsions (Dickinson 2008; Rezvani, Taherian, and Schleining 2011; Homayoonfal, Khodaiyan, and Mousavi 2015).

Relationship between the chemical composition of BGN SDFs and emulsion behaviour

In order to describe the differences in emulsion behaviours, the characterization of SDFS isolated from different varieties of BGN was carried out. Tables 3 gives the oil binding capacity (OBC) and sugar composition of BGN SDFs and Table 4 gives the consistency coefficient (K) and hysteresis loop areas of BGN SDF solutions. The higher stability of brown-eye and black-eye SDF stabilized emulsions could be attributed to the high neutral sugar composition of these BGN SDFs (Table 3). Gallegos, Franco, and Partal (2004) reported an increase in stability of emulsion systems associated with increasing sugar composition. Arabinose, galactose and xylose were present in higher quantities in black-eye and brown-eye SDFs (Maphosa and Jideani 2016) and this is suggestive of the presence of arabinogalactans and arabinoxylans in higher quantities. These carbohydrates are reported to increase the viscosity of systems and to increase their stability (Saeed et al. 2011; Khotimchenko et al. 2012).

Black-eye and brown-eye SDFs were also shown to have higher OBCs of 3.84 and 4.03 g oil/g fibre, respectively while red and brown SDFs had lower OBCs of 3.72 and 2.78 g oil/g fibre, respectively (Maphosa and Jideani 2016). Polysaccharides with higher OBCs bind the oil phase of the emulsion more than those with lower OBCs. The OBCs of BGN SDFs could therefore explain the more dispersed emulsion systems stabilized with black-eye and brown-eye SDFs.

The bulk and direct densities of BGN SDFs were significantly lower for black-eye and brown-eye SDFs (Table 4), suggesting that the molecular particles of these fibres have the ability to pack more closely together and thus would be expected to stay intact longer than brown and red SDFs (Diedericks 2014).

The consistency coefficient and hysteresis loop areas (Table 4) of BGN SDFs could also be used to describe the behaviour of the emulsions. The hysteresis loop area gives an indication of the structural breakdown, with higher values indicating more extensive damage (Adeyi 2014). Black-eye and brown-eye SDFs showed the least structural damage by shearing with time (Table 4). The consistency coefficient (K), which describes the viscosity of a system with higher values, indicates more viscous solutions (Adeyi 2014). The consistency coefficient was observed to be highest for brown-eye SDF (0.0064 Pa s^n) and lowest for red SDF (0.0026 Pa s^n).

Table 3: Neutral sugar composition of Bambara groundnut soluble dietary fibres.

	Sugars (%)						
Variety	Arabinose/Galactose	Fructose	Fucose	Glucose	Mannose	Xylose	Total sugar
Black-eye	19.6 ± 0.9^{a}	1.3 ± 0.1^{a}	0.3 ± 0.1^{a}	1.0 ± 0.1^{a}	6.1 ± 0.5^{a}	16.6 ± 1.6^{a}	44.8
Brown-eye	15.2 ± 1.5^{b}	1.5 ± 0.1^{ab}	0.3 ± 0.1^{a}	0.8 ± 0.1^{ab}	6.5 ± 0.2^{a}	15.6 ± 0.2^{ab}	39.8
Brown	9.4 ± 0.1^{c}	1.7 ± 0.1^{b}	0.1 ± 0.0^{b}	0.8 ± 0.1^{ab}	7.4 ± 0.6^{b}	13.0 ± 1.8^{c}	32.5
Red	10.0 ± 0.6^{c}	1.6 ± 0.1^{b}	0.3 ± 0.0^{a}	0.6 ± 0.2^{b}	5.0 ± 0.3^{c}	13.7 ± 0.8^{bc}	31.2

Values are mean ± standard deviation. Means within a column followed by the same superscript are not significantly [$p > 0.05$] different. OBC: Oil binding capacity; HPP: Hydrolyzable polyphenols.

Table 4: Power law model parameters and hysteresis loop areas of four Bambara groundnut soluble dietary fibres.

Concentration (8%)	K ($Pa \cdot s^{n}$)	Hysteresis loop area (Pas^{-1})	Bulk density (g/mL)	Direct density (g/mL)	Oil binding capacity (g/g)
Black-eye	0.0031 ± 0.0^{a}	5.54 ± 0.2^{a}	0.4560 ± 0.0^{a}	0.0546 ± 0.0^{a}	3.84 ± 0.0^{a}
Brown-eye	0.0064 ± 0.0^{b}	3.46 ± 0.0^{b}	0.4570 ± 0.0^{a}	0.0551 ± 0.0^{b}	4.03 ± 0.1^{b}
Brown	0.0031 ± 0.0^{a}	6.45 ± 0.0^{c}	0.5017 ± 0.0^{b}	0.0696 ± 0.0^{c}	3.72 ± 0.1^{a}
Red	0.0026 ± 0.0^{c}	13.51 ± 0.1^{d}	0.5024 ± 0.0^{c}	0.1132 ± 0.0^{d}	2.78 ± 0.1^{c}

Values are mean ± standard deviation. K: consistency coefficient; n: flow behaviour index; R^2: coefficient of determination.

This gave an indication that brown-eye SDF was a more stable system, whereas red SDF was less stable.

BGN SDFs have high fat binding properties, are rich in polyphenolic compounds, have a high sugar composition, are bland in taste and have a light colour (Maphosa and Jideani 2016). As such, the application of BGN SDFs in food model systems will not only increase the utilization and consequently the market value of BGN but will also be significant in improving the quality of the emulsion systems without affecting the sensory properties.

Conclusions

This study confirmed that BGN-SDFs can be successfully used as beverage emulsion stabilizers. Black-eye and brown-eye SDFs form more stable emulsions than brown and red SDFs. BGN-SDF stabilized emulsions are stable to creaming and destabilized mainly by phenomenon involving oil droplet aggregation. Each emulsion behaves slightly differently due to compositional differences. Turbidity loss rate is largely influenced by the average droplet sizes of the emulsions.

Funding

The authors acknowledge the Cape Peninsula University of Technology University Research Funding (CPUT-URF) and the National Research Foundation (NRF) for financial assistance towards the research running costs. Bambara groundnut dietary fibre is a patent of CPUT (South Africa complete patent, 2014/04371).

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