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Polyphenols from *Allanblackia floribunda* seeds: Identification, quantification and antioxidant activity

Grace A. Akpanika [a], Ana Winters [b], Thomas Wilson [b], Gloria A. Ayoola [a], Aderonke A. Adepoju-Bello [b], Barbara Hauck [b,*]

[a] Department of Pharmaceutical Chemistry, Faculty of Pharmacy, University of Lagos, Nigeria
[b] Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Gogerddan, Aberystwyth SY23 3EB, UK

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ABSTRACT

Oil rich seeds of *Allanblackia floribunda*, a tree from tropical Africa, have traditionally been used in food preparation. Furthermore, the therapeutic properties of various parts of this tree have long been exploited in traditional medicine. As both food and pharmaceutical industries show growing interest in tropical tree crops, this study aimed to investigate whether *A. floribunda* seeds could also be used as a source of potentially bioactive compounds. The polyphenol profile revealed six predominant compounds which were identified by HPLC-PDA-ESI/MS^n as the biflavonoids morelloflavone, Gb-2a and volkensiflavone and their respective glucosides. A range of less abundant flavones, flavonols and flavan-3-ols was also detected. All six major compounds showed antioxidant activity, with the activity of morelloflavone, its glucoside and Gb-2a-glucoside comparable with that of ascorbic acid. The main compounds accounted for approximately 10% of dry weight, making the seeds used for oil production a rich source of biflavonoids as a by-product.

1. Introduction

Allanblackia floribunda Oliv (Clusiaceae or Guttiferae) is an evergreen tree which grows in the tropical rainforests of Africa to a height of up to 30 m and is traditionally used in a variety of ways (Orwa & Munjuga, 2007; Orwa et al., 2009). Whilst the seeds consist to over 60% of oil and provide edible vegetable fat (Orwa et al., 2009; Wilfred, Adubofuor, & Oldham, 2010), various parts of the tree, including roots and bark, are used in traditional medicine for the treatment of a range of ailments such as toothache, dysentery and coughs (Betti, 2004; Kayode, 2006; Olowokudejo, Kadiri, & Travih, 2008). Furthermore, *Allanblackia floribunda* extracts have been reported to exhibit antimicrobial, anti-inflammatory and antioxidant activity (Ajibesin, Rene, Bala, & Essiett, 2008; Ayoola et al., 2008; Ayoola et al., 2009; Kuete et al., 2011) as well as potential antimalarial (Azebaze et al., 2015) and anticancer effects (Fadeyi, Fadeyi, Adejumo, Okoro, & Myles, 2013). To date, a range of potentially bioactive compounds have been reported in a variety of extracts from *Allanblackia floribunda* and related species, including benzophenones, xanthones and biflavonoids (Fuller, Blunt, Boswell, Cardellina, & Boyd, 1999; Locksley & Murray, 1971; Nkengfack, Azebaze, Vardamides, Fomum, & van Heerden, 2002). In the seed, the focus has mainly been on oil, with some information available on antioxidative properties of *A. floribunda* seed cake (Boudjeko, Ngomoyogoli, Woguia, & Yanou, 2013). With growing interest in *Allanblackia* species as tree crop in particular for the food industry (IUCN, 2014), the aim of this study was to investigate the polyphenol profile of *A. floribunda* seeds in order to establish whether seed remnants after plant oil extraction could be a source of bioactive compounds with interest to the pharmaceutical sector.

* Corresponding author.
E-mail addresses: gakpanika@yahoo.com (G.A. Akpanika), alg@aber.ac.uk (A. Winters), tpw2@aber.ac.uk (T. Wilson), gayoola@unilag.edu.ng (G.A. Ayoola), aadepoju-bello@unilag.edu.ng (A.A. Adepoju-Bello), bdh@aber.ac.uk (B. Hauck).

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2. Materials and methods

2.1. Plant material and reagents

Fruits of *Allanblackia floribunda* were collected in three different years from uncultivated farmland in Oke Igbo, Ondo State, South Western Nigeria. The fruits were authenticated at the Forestry Research Institute of Nigeria (FRIN), Ibadan (voucher specimen number FHI107929). Seeds were separated from the mesocarp, and air-dried seeds were crushed, freeze-dried and milled into a fine powder (⩽1.0 mm) with an automated bespoke ball mill robot (Labman Automation, Middlesbrough, UK). Briefly, three stainless steel balls (3 mm diameter) were added to approximately 200 mg seeds in a 2 mL microtube and shaken in the robot at the predetermined speed and duration to achieve the desired particle size.

HPLC grade solvents for extraction and analysis of phenolics were purchased from VWR (Lutterworth, Leicestershire, UK). Response factors for quantification were obtained using flavonoid standards with a minimum of 98% purity (Carbosynth Ltd, Compton, Berkshire, UK). All other analytical standards and chemicals were purchased from Sigma Aldrich (Gillingham, Dorset, UK).

2.2. Extraction of soluble phenolics

Soluble phenolics were extracted from approximately 20 mg seed powder by shaking with 5 ml 70% methanol for 15 min at room temperature. The sample was then centrifuged for 10 min at 1700*g*, the supernatant decanted and the pellet extracted twice more. Methanol was removed from the combined supernatants under vacuum at 60 °C before extracts were partially purified by solid phase extraction (SPE) using Sep-Pak C_{18} cartridges (Waters Ltd, Elstree, UK) as described by Hauck, Gallagher, Morris, Leemans, and Winters (2014) and dried under vacuum at 60 °C. Prior to further analysis, samples were typically dissolved in 0.5 ml 70% methanol and diluted as necessary.

2.3. Liquid chromatography-tandem mass spectrometry

Secondary metabolites were analysed by reverse-phase high performance liquid chromatography with online photodiode array detection and electrospray ionisation–ion trap tandem mass spectrometry (HPLC-PDA-ESI/MS^n). Structural elucidation was performed on a Thermo Finnigan LC-MS system (Thermo Electron Corp, Waltham, MA, USA) comprising a Finnigan PDA Plus detector, a Finnigan LTQ linear ion trap with ESI source and a Waters C_{18} Nova-Pak column (3.9 × 100 mm, particle size 4 μm), with column oven temperature maintained at 30 °C. The PDA scan range was set to 240–400 nm, and injection volume was typically 10 μl. The mobile phase consisted of water with 0.1% formic acid (solvent A) and methanol with 0.1% formic acid (solvent B). The column was equilibrated with 95% solvent A at a flow rate of 1 ml min^{-1}, with 10% going to the mass spectrometer, and the percentage of solvent B increased linearly to 65% over 60 min. MS parameters were as follows: sheath gas 30, auxiliary gas 15 and sweep gas zero (arbitrary units), spray voltage −4.0 kV in negative and 4.8 kV in positive ionisation mode, capillary temperature 320 °C, capillary voltage −1.0 V and 45 V, respectively, tube lens voltage −68 and 110 V, respectively, and normalised collision energy (CE) typically 35%.

Accurate mass measurements only were carried out on an Orbitrap Fusion Tribrid mass spectrometer (Thermo Fisher Scientific, Waltham, MA, USA) with heated ESI source coupled to a Dionex UltiMate 3000 ultra high performance liquid chromatography (UHPLC) system (Thermo Fisher Scientific). Chromatographic separation was performed on a reverse-phase C_{18} Hypersil Gold column (20 × 2.1 mm, particle size 1.9 μm; Thermo Fisher Scientific) which was maintained at a temperature of 60 °C and with solvents A and B as described above. The column was equilibrated with 95% solvent A at a flow rate of 0.4 ml min^{-1}, and the percentage of solvent B increased linearly to 100% over 7 min, followed by isocratic elution at 100% solvent B for 3.5 min. High resolution mass spectra were acquired in both negative and positive ionisation mode at a resolution of 120,000 with an automatic gain control (AGC) target of $2e^5$ and a maximum injection time of 100 ms, with other MS parameters as follows: vaporiser temperature 358 °C, spray voltage −2.5 kV in negative and 3.5 kV in positive ionisation mode, sheath gas 45, auxiliary gas 13 and sweep gas 1 (arbitrary units) and capillary temperature 342 °C.

2.4. Quantification of predominant compounds

For quantification of the predominant compounds, seed samples harvested in three different years were extracted in triplicate as described in Section 2.2, followed by reverse-phase HPLC. The system comprised a Waters 996 PDA detector and a Waters C_{18} Nova-Pak radial compression column (8 × 100 mm, particle size 4 μm), with chromatographic conditions as described by Hauck et al. (2014) and detection wavelength set to 280 nm. Response factors (RF) for the flavonoid monomers naringenin, eriodictyol, apigenin and luteolin were obtained from linear standard curves over the range of 0.2–10 μg of standard and calculated as

$$RF = \text{amount } [\mu g]/\text{peak area}_{280nm}.$$

All response curves had linear regression coefficients >0.996.

Response factors of biflavonoid aglycones were calculated as the mean of the relevant flavonoid monomer RFs, and for the quantification of biflavonoid glucosides these values were multiplied by the following correction factor to allow for the difference in molecular weight (M_r):

$$(M_{r\ aglycone} + 162)/M_{r\ aglycone}.$$

2.5. Acid hydrolysis and analysis of sugar moieties and flavonoid aglycones

To identify the aglycone part of the flavonoid glycosides, acid hydrolysis of total extract was carried out by combining equal volumes of aqueous extract and 2 mol L^{-1} HCl. After heating the solution to 90 °C for 1 h, the pH was adjusted to 3–4 with NaOH prior to partial purification by SPE as described in Section 2.2. Flavonoid aglycones were then analysed by HPLC-PDA-ESI/MS^n as described in Section 2.3 and identified by direct comparison with relevant flavonoid standards.

For identification of the sugar moieties of the main glycosylated metabolites, compounds were purified by collecting the HPLC eluent of individual peaks from the Waters system described in Section 2.4. After reducing the volume under vacuum at 60 °C acid hydrolysis was performed by combining equal volumes of aqueous extract and 2 mol L^{-1} HCl. The solution was heated to 90 °C for 1 h and subsequently the pH was adjusted to 6–7 with NaOH. The samples were then loaded onto Strata-X-A strong anion exchange columns (Phenomenex, Macclesfield, UK) which had been conditioned with 100% methanol and equilibrated with water. The sugar containing non-binding fraction of the samples was collected for further analysis.

Monosaccharides were analysed by high-performance anion-exchange chromatography with pulsed amperometric detection (HPAEC-PAD). Separation of monosaccharides was achieved on a Dionex ICS-5000 system (Thermo Fisher Scientific, Waltham, MA, USA) fitted with an Eluent Generator and a Dionex CarboPac

SA10 column (250 × 4 mm; Thermo Fisher Scientific) with an SA-10 guard column (50 × 4 mm). The operating temperature of the column was 45 °C with an isocratic mobile phase of 1 mmol L^{-1} KOH pumped at a rate of 1.5 ml min^{-1}. Monosaccharides were identified by comparison of retention times with glucose and galactose standards.

2.6. Antioxidant activity of selected metabolites

The predominant metabolites were purified by collecting the HPLC eluent of individual peaks from the Waters system described in Section 2.4 and then dried down and resuspended in 50% methanol at a concentration of 100 μg mL^{-1}. The antioxidant activity of individual compounds was measured in triplicate by 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay (Brand-Williams, Cuvelier, & Berset, 1995) and by ferric ion reducing antioxidant power (FRAP) assay (Benzie & Strain, 1996).

For the DPPH assay, 0.5 mL of DPPH solution (140 μmol L^{-1} in 50% methanol) was combined with an equal volume of sample at a concentration of 5–100 μg mL^{-1} and left to stand at room temperature for 30 min. After this time absorbance (A) was measured on a Pharmacia Biotech Ultraspec 4000 UV/Visible spectrophotometer (Amersham Pharmacia Biotech, Little Chalfont, UK) at 517 nm, including 50% methanol as control, and% inhibition (I) was determined as

$$I = (A - A_{blank})_{control} - (A - A_{blank})_{sample}/(A - A_{blank})_{control} \times 100$$

with IC_{50} defined as the concentration which resulted in 50% inhibition.

The FRAP assay measures reduction of the Fe^{3+}/tripyridyl-s-triazine complex (TPTZ) to the blue ferrous form and was performed as follows: acetate buffer (300 mmol L^{-1}, pH 3.6), TPTZ (10 mmol L^{-1} in 40 mmol L^{-1} HCl) and ferric chloride (20 mmol L^{-1}) were mixed in the ratio of 10: 1: 1 to obtain the FRAP reagent. Sample volumes of 125 μL at a concentration of 100 μg mL^{-1} were added to 1 ml FRAP reagent and after 10 min absorbance was measured at 593 nm. A ferric chloride calibration curve ranging from 100 to 1000 μmol L^{-1} was prepared to estimate Fe^{2+} concentration.

2.7. Statistical analysis

Quantitative analyses were carried out in triplicate and results are presented as mean ± standard error of the mean. Where appropriate results were statistically analysed by one-way ANOVA and significant differences were determined by the Bonferroni post hoc test, GenStat 14th edition.

3. Results and discussion

3.1. Phenolic profile

Fig. 1 shows the profile of soluble polyphenols extracted from *Allanblackia floribunda* seeds which showed little variation between years. Analysis by HPLC-PDA-ESI/MS^n revealed six abundant and a range of minor compounds which were tentatively identified based on their UV/vis absorbance and mass spectral characteristics summarised in Tables 1 and 2 and Fig. 2. The compounds which were identified all belonged to the flavonoids, with biflavonoids as the main class. The main compounds were collected individually from peaks 1 to 6 (Fig. 1) and purified as pale yellow to orange crystalline powders. Molecular weights (M_r) of the main compounds are based on accurate mass measurements in both negative and positive ionisation mode, whilst M_r of less abundant compounds are nominal mass based on general MS scans

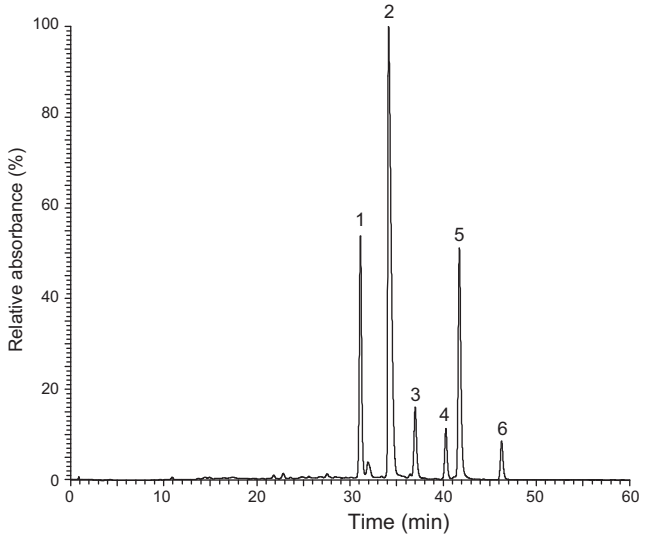

Fig. 1. HPLC chromatogram of soluble secondary metabolites from *Allanblackia floribunda* seeds detected by photodiode array at 280 nm. Peak numbering refers to the six predominant compounds.

in both ionisation modes. MS^n analyses were carried out in negative ionisation mode unless stated otherwise.

3.1.1. Identification of biflavonoids

Based on accurate mass data (Table 2) compound 5 was assigned the elemental composition $C_{30}H_{20}O_{11}$ with M_r 556.1005 Da. The corresponding UV/vis spectrum showed absorbance maxima at 275(sh), 290 and 348 nm, a combination of the absorbance spectrum typical of a flavone (with two major absorption bands in the region of 300–380 nm for band I and 240–280 nm for band II; Mabry, Markham, & Thomas, 1970) with that of a flavanone (with predominant absorption band II and a much reduced band I) and in close agreement with the absorbance characteristics reported for the biflavonoid morelloflavone, a naringenin-luteolin conjugate (Herbin, Jackson, Locksley, Scheinmann, & Wolstenholme, 1970). MS^2 fragmentation of the parent ion at *m/z* 555 in negative mode resulted in loss of 126 Da, yielding one main product ion with *m/z* 429. This can be attributed to cleavage of ring C (Fig. 3a), typical of the fragmentation of flavonoids (Cuyckens & Claeys, 2004; Fabre, Rustan, de Hoffmann, & Quetin-Leclercq, 2001), here breaking bonds 1 and 4 and producing fragment ion $[M-H-^{1,4}A]^-$ with the remainder of the upper moiety of the dimer still attached to the lower moiety. A low intensity fragment with *m/z* 403 was also observed. This corresponds to loss of 152 Da and stems from cleavage of bonds 1 and 3 of ring C. Fragmentation of naringenin standard in negative mode showed cleavage of corresponding bonds, yielding ion $^{1,3}A^-$ with *m/z* 151 as base peak and ion $^{1,3}B^-$ with *m/z* 119 among the less intense fragment ions. In the dimer, ring B is still attached to the lower moiety, thus resulting in fragment $[M-H-^{1,3}A]^-$. The minor fragments also included ions at *m/z* 449 (loss of 106 Da) and *m/z* 461 (loss of 94 Da, $[M-H-B]^-$), and corresponding losses were also seen when fragmenting naringenin standard.

With normalised collision energy (CE) set to default (35%), MS^3 fragmentation of the predominant MS^2 ion at *m/z* 429 occurred only to a small extent, an observation also made with luteolin standard. Raising CE to 70% resulted in the neutral loss of a number of small molecules such as CO, CO_2 and H_2O, also typical of flavonoid fragmentation (Cuyckens & Claeys, 2004; Fabre et al., 2001). A further MS^3 product ion with *m/z* 295 (loss of 134 Da) can be

Table 1
Polyphenolic compounds detected in *Allanblackia floribunda* seed extract by HPLC-PDA-ESI/MS^n.

t_R (min)	λ_{max} (nm)	M_r	MS^2 fragments in −ve mode unless stated otherwise (base peak in bold)	MS^3 fragments of MS^2 base peak (base peak in bold)	Additional diagnostic MS^n fragments (parent ion in bracket)	Tentative ID (Fig. 1 peak No. in brackets)
10.9	279	578	287, 289, 407, **425**, 451, 559		179, 205, 245 (289)	Epicatechin dimer
13.7	279	290	179, 205, **245**			Epicatechin[1]
14.4	279	866	407, 425, 451, 575, 577, **695**, 713, 739		287, 289 (577) 179, 205, 245 (289)	Epicatechin trimer
14.9	279	1154	575, 577, 739, 863, **865**, 983, 1001, 1027, 1135		245, 287, 289 (577)	Epicatechin tetramer
21.8	nd	736	429, **447**, 573	269, 385, 403, 419, **429**	419, 421, 429, 447, 467, 479 (573)	Hexoside of biflavonoid at t_R 30.9 min
22.8	nd	442	139, 143, 161, 179, 205, 217, 235, **330/331**, 397			Unidentified compound
		578	287, 289, 407, **425**, 451, 559		179, 205, 245 (289)	Epicatechin dimer
23.6	nd	624	**285**, 327, 489			Luteolin-hexosyl-glucuronate
			287, 463 (+ve mode)			
24.9	nd	578	293, 311, 341, **413**, 457			Apigenin-2″-*O*-rhamnosyl-*C*-hexoside
25.6	nd	462	**285**			Luteolin-glucuronate
		1008	431, 557, 719, 837, 845, **855**, 881	431, 649, 675, 811, **837**	431, 557, 593 (719)	Gb-2a conjugate
26.8	nd	608	**269**			Apigenin-hexosyl-glucuronate
			271, 447 (+ve mode)			
27.5	nd	880	**717**	403, 429, 493, 537, 555, **565**, 591	295 (429)	Morelloflavone-dihexoside
		610	**301**			Quercetin-rhamnosyl-hexoside
			303, 449, 465 (+ve mode)			
28.4	nd	1006	717, 809, 835, **853**, 879	809, **835**	429, 493, 537, 555, 565, 591, 623 (717)	Morelloflavone conjugate
29.6	nd	756	**285**, 575, 593			Luteolin-rhamnosyl-dihexoside
			287, 449, 595, 611 (+ve mode)			
30.2	nd	1008	431, 557, 719, 837, 845, **855**, 881	431, 649, 675, 811, **837**	431, 557, 593 (719)	Gb-2a conjugate
30.9	nd	574	**447**	269, 295, 325, 403, **419**, 429	421, 467, 479 (573)	Unidentified biflavonoid
31.1	288	720	**431**, 557, 593	269, **295**, 413, 321	405, 431, 451, 463 (557) 625 (719)	Gb-2a-glucoside (1)
31.3	nd	578	**269**			Apigenin-rhamnosyl-hexoside
			271, 433 (+ve mode)			
31.9	nd	594	**285**			Kaempferol-rhamnosyl-hexoside (leading edge)
			287, 449 (+ve mode)			
		594	**285**			Luteolin-rhamnosyl-hexoside (trailing edge)
			287, 449 (+ve mode)			
34.1	274, 290, 351	718	429, 493, 537, 555, **565**, 591, 623	**403**, 445	403, 449, 461 (555) 295 (429) 623 (717)	Morelloflavone-glucoside (2)
36.4	nd	704	389, **415**, 447, 523, 541, 551, 577, 609	**295**, 321, 269	389, 415, 435, 447 (541)	Dinaringenin-hexoside
37.0	293	558	**431**	269, **295**, 321, 413	405, 451, 463 (557)	Gb-2a (3)
37.2	nd	610	**463**, 301			Quercetin-rhamnosyl-hexoside
38.0	nd	286	151, 175, 197, 199, 201, 213, 217, **241**, 243, 257, 267			Luteolin[1]
40.3	274, 290, 330	702	413, 433, 445, 521, **539**, 575	387, **413**, 433, 445	295 (413)	Volkensiflavone-glucoside (4)
41.2	nd	594	**285**, 447			Kaempferol-rhamnosyl-hexoside
41.6	nd	542	389, **415**, 435, 447	269, **295**, 309, 321		Dinaringenin
41.7	275(sh), 290, 348	556	**429**	295, 357, 385, **401**	403, 449, 461 (555)	Morelloflavone (5)
46.3	274(sh), 290, 328	540	387, **413**, 433, 445	293, 295, 369, **385**		Volkensiflavone (6)

nd: not detected, either due to low absorbance or coeluting compounds.
[1] Identified by direct comparison with reference compounds.

accounted for by cleavage of bonds 1 and 3 of the heterocycle of the luteolin moiety, producing $[M-H-^{1,4}A-^{1,3}E]^-$. Cleavage of corresponding bonds was also observed in luteolin standard, resulting in a fragment with m/z 151. Overall, fragmentation of the flavonoid dimer mirrored a combination of the fragmentation patterns observed for naringenin and luteolin standards. The data presented here is in close agreement with mass spectral data reported by Carrillo-Hormaza et al. (2016) and supports the tentative identification of compound 5 as morelloflavone (naringenin-I,3-II,8-luteolin).

Table 2
Accurate mass and content of predominant biflavonoids in seeds of *Allanblackia floribunda*.

Fig. 1 peak no. (compound ID)	t_R (min)	Measured mass $[M-H]^-$	Calculated mass $[M-H]^-$	Mass difference (ppm)	Measured mass $[M-H]^+$	Calculated mass $[M-H]^+$	Mass difference (ppm)	Content (μg mg^{-1} seed powder)
1 (Gb-2a-glucoside)	30.1	719.1615	719.1618	0.42	721.1774	721.1763	1.53	16.73 ± 0.906
2 (morelloflavone-glucoside)	33.7	717.1459	717.1461	0.28	719.1616	719.1607	1.25	58.26 ± 3.872
3 (Gb-2a)	35.4	557.1087	557.1089	0.36	559.1238	559.1235	0.54	2.75 ± 0.146
4 (volkensiflavone-glucoside)	39.2	701.1514	701.1512	0.29	703.1666	703.1657	1.28	4.03 ± 0.297
5 (morelloflavone)	40.3	555.0929	555.0933	0.72	557.1079	557.1078	0.18	16.54 ± 0.935
6 (volkensiflavone)	44.5	539.0984	539.0984	0.00	541.1134	541.1129	0.92	2.02 ± 0.136

The content of individual compounds is expressed as mean ± standard error of the mean (n = 9).

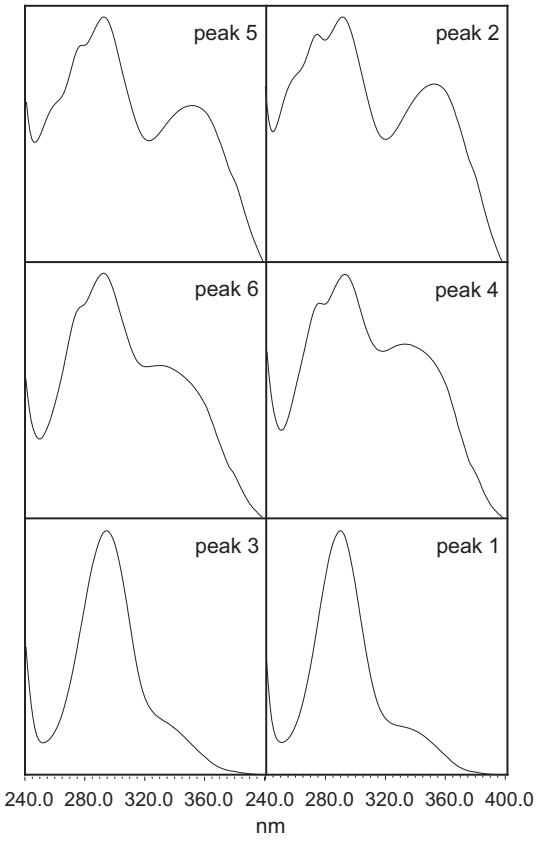

Fig. 2. UV/vis spectra of biflavonoids from *Allanblackia floribunda* seeds.

The UV/vis spectrum of peak 6 showed absorbance maxima at 274, 290 and 328 nm (Fig. 2), similar to those of peak 5 but with absorbance band I at a lower wavelength, consistent with the absorbance characteristics reported for volkensiflavone, a naringenin-apigenin conjugate (Herbin et al., 1970). Accurate mass measurements (Table 2) suggest the elemental composition $C_{30}H_{20}O_{10}$ with M_r 540.1056 Da for this compound. The fragmentation pattern in negative mode was also similar to that of morelloflavone (Table 1, Fig. 3a) and yielded product ions consistent with a naringenin moiety, namely $[M-H-^{1,4}A]^-$ with m/z 413, $[M-H-B]^-$ with m/z 445, $[M-H-106]^-$ with m/z 433 and $[M-H-^{1,3}A]^-$ with m/z 387, whereas fragmentation of the MS^2 base peak at m/z 413 with raised CE resulted in losses similar to those observed with apigenin standard, yielding product ions at m/z 295 (loss of

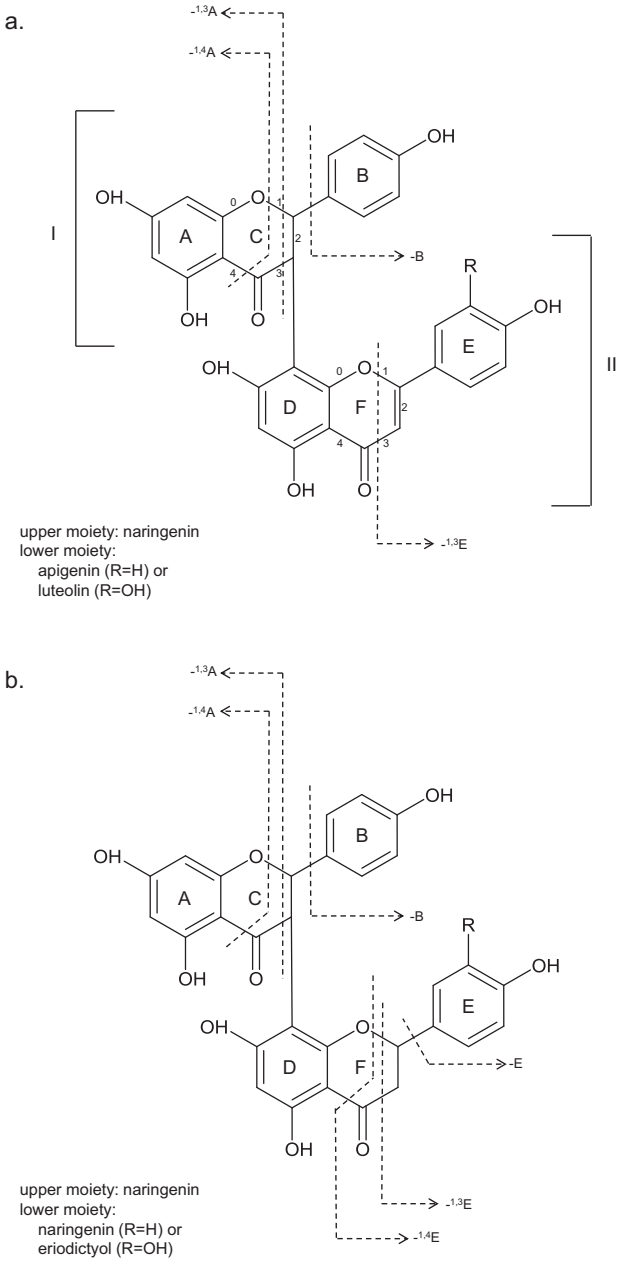

Fig. 3. Structures and fragmentation patterns of (a) flavanone-flavone dimers (volkensiflavone, morelloflavone) and (b) flavanone-flavanone dimers (Gb-2a, dinaringenin) extracted from *Allanblackia floribunda* seeds.

118 Da, [M−H−^{1,4}A−^{1,3}E]$^-$) and 293 (loss of 120 Da). The findings for compound 6 are in close agreement with the fragmentation pattern reported for volkensiflavone (naringenin-I,3-II,8-apigenin) by Carrillo-Hormaza et al. (2016).

The UV/vis spectrum of peak 3 (Fig. 2) showed a band II absorbance maximum at 293 nm with band I reduced to a small shoulder, a characteristic of flavanones (Mabry et al., 1970). Based on accurate mass measurements (Table 2) the molecular formula $C_{30}H_{22}O_{11}$ with M_r 558.1162 Da was assigned to this compound. Fragmentation in negative ionisation mode followed a pattern very similar to that described above (Table 1, Fig. 3b). MS^2 analysis of the parent ion at *m*/*z* 557 yielded a predominant product with *m*/*z* 431 (loss of 126 Da, [M−H−^{1,4}A]$^-$) as well as low abundance ions consistent with the loss of 152 Da (at *m*/*z* 405), 106 Da (at *m*/*z* 451) and 94 Da (at *m*/*z* 463) from a naringenin moiety. MS^3 analysis of the fragment at *m*/*z* 431 produced a base peak with *m*/*z* 295 (loss of 136 Da, [M−H−^{1,4}A−^{1,3}E]$^-$) and less intense ions at *m*/*z* 269 (loss of 162 Da, [M−H−^{1,4}A−^{1,4}E]$^-$; Fabre et al., 2001) and 321 (loss of 110 Da, [M−H−^{1,4}A−E]$^-$), in agreement with the fragmentation pattern observed for eriodictyol standard. Based on the data presented here compound 3 was tentatively identified as Gb-2a (naringenin-I,3-II,8-eriodictyol), a conclusion supported by the mass spectral data of Carrillo-Hormaza et al. (2016).

Peaks 1, 2 and 4 had UV/vis spectra which were almost identical to those of peaks 3, 5 and 6, respectively (Fig. 2) but with M_r 162 Da bigger than the corresponding biflavonoids (Tables 1 and 2), and they were also more polar as shown by the earlier retention times. The MS^2 spectra of the compound 1, 2 and 4 parent ions included products [M−H−162]$^-$, indicating the loss of an *O*-linked hexose (Vukics & Guttman, 2010), while other product ions resulted from fragmentation of the biflavonoid core with or without simultaneous loss of the sugar moiety. In addition, MS^n fragmentation of the presumed aglycone fragments at *m*/*z* 557, 555 and 539, respectively, followed the common pattern seen for compounds 3, 5 and 6, thus confirming biflavonoids as core molecules of the glycosides, with neutral loss of 126 Da producing the diagnostic fragments [M−H−162−^{1,4}A]$^-$, while subsequent MS^n analysis included product ions [M−H−162−^{1,4}A−^{1,3}E]$^-$ with *m*/*z* 295.

HPAEC analysis of the purified, hydrolysed compounds revealed glucose as the sugar moiety of all three glycosides. Although it is not possible to determine the precise position of the glucose part with the methods employed here, fragmentation data for compounds 1 and 2, which have different substitution patterns on rings B and E, suggests that the glucose may be attached to one of the hydroxyl groups of the lower flavonoid unit. In the MS^2 spectra of both compounds there were product ions characteristic for the fragmentation of the naringenin moiety with the sugar unit still attached, namely [M−H−^{1,4}A]$^-$ (loss of 126 Da), [M−H−^{1,3}A]$^-$ (loss of 152 Da) and low intensity ions indicating the loss of ring B ([M−H−B]$^-$, loss of 94 Da).

Analysis of the smaller peaks revealed further compounds of this type. In particular, a compound with M_r 542 Da eluting at 41.6 min followed a similar fragmentation pattern as described above (Fig. 3b) and was tentatively identified as dinaringenin, and a hexoside of this with M_r 704 Da was found at t_R 36.4 min. A further biflavonoid with M_r 574 Da eluted at t_R 30.9 min and had a fragmentation pattern consistent with naringenin as upper and an unidentified flavonoid with M_r 304 Da as lower unit, and a hexoside of this with M_r 736 was seen at 21.8 min. In addition to morelloflavone and morelloflavone-glucoside, a compound with M_r 880 Da eluting at 27.5 min showed a fragmentation pattern consistent with morelloflavone-dihexoside. Some larger related molecules were also detected amongst the low abundance compounds. For example, fragmentation of a compound with M_r 1006 Da at t_R 28.4 min produced a fragment ion with *m*/*z* 717. Further MS^3 analysis of this fragment was consistent with morelloflavone-hexoside, and the compound was tentatively identified as morelloflavone conjugate. Similarly, MS^2 analysis of two compounds with M_r 1008, eluting at 25.6 and 30.2 min, produced fragments with *m*/*z* 719, and MS^3 analysis of this ion product was consistent with the fragmentation pattern of Gb-2a-hexoside.

Both morelloflavone and volkensiflavone have previously been reported in *A. floribunda* heartwood (Locksley & Murray, 1971) and stem bark (Brusotti et al., 2016) as well as in various tissues of related genera such as fruits, leaves and heartwood of *Garcinia* (Carrillo-Hormaza et al., 2016; Herbin et al., 1970; Stark et al., 2015; Yang et al., 2010). Whilst Gb-2a is also well documented in *Clusiaceae* (Carrillo-Hormaza et al., 2016; Herbin et al., 1970; Stark et al., 2015), this is to our knowledge the first report of Gb-2a in *Allanblackia*.

3.1.2. Identification of other flavonoids

In addition to the biflavonoids discussed in Section 3.1.1, a range of low abundance compounds from different flavonoid classes were also detected (Table 1). Epicatechin and luteolin were identified by direct comparison with analytical standards. Due to the absence of catechin in the extract, the flavan-3-ol oligomers found at several retention times were assumed to consist of epicatechin units. There was also a range of flavone and flavonol glycosides which were tentatively identified by their fragmentation patterns following the principles outlined by Vukics and Guttman (2010) and Ferreres, Gil-Izquierdo, Andrade, Valentão, and Tomás-Barberán (2007), whilst their flavonoid cores were confirmed by MS^n analyses and acid hydrolysis. Interestingly, *A. floribunda* seed extract did not contain detectable amounts of xanthones or benzophenones which were previously reported in other tissues of *A. floribunda* and other species of the *Clusiaceae* family (Azebaze et al., 2009; Fuller et al., 1999; Locksley & Murray, 1971; Nkengfack et al., 2002; Yang et al., 2010).

3.2. Characterisation of biflavonoids

3.2.1. Quantification

The six main biflavonoids were quantitated in μg mg^{-1} seed powder using response factors based on HPLC standard curves obtained with analytical standards as described in Section 2.4. The total biflavonoid content was high, constituting approximately 10% of dried seed powder in comparison to seeds of the related species *Garcinia madruno* where Carrillo-Hormaza et al. (2016) reported a total biflavonoid content of less than 2%. Morelloflavone and its glucoside were the main biflavonoids present in *A. floribunda seeds* (Table 2). Similarly, Locksley and Murray (1971) reported morelloflavone as the predominant metabolite in *A. floribunda* heartwood.

3.2.2. Antioxidant activity

The antioxidant activities of the six main biflavonoids were analysed by the DPPH-radical scavenging and the ferric reducing antioxidant power (FRAP) assays. All six compounds demonstrated antioxidant activity which differed significantly ($P \leqslant 0.05$) and showed a similar ranking of activity with both assays apart from Gb-2a aglycone and volkensiflavone-glucoside whose order was reversed with the DPPH compared with the FRAP assay (Table 3). The highest activities were observed with Gb-2a and morelloflavone-glucosides and the lowest activities with volkensiflavone aglycone, volkensiflavone-glucoside and Gb-2a aglycone. Morelloflavone-glucoside and aglycone and GB-2a-glucoside showed radical scavenging activities comparable with ascorbic acid (IC_{50} values 16.87, 21.26, 18.38 and 19.36 μg ml^{-1}, respectively). Radical scavenging and FRAP activities observed with morelloflavone aglycone and glucoside also reflect results reported by Kuete et al. (2011) and Carrillo-Hormaza et al. (2016) where the

Table 3
Antioxidant capacity of biflavonoids from *A. floribunda* seeds.

Fig. 1 peak no. (compound ID)	FRAP (μmol Fe^{2+} mg^{-1})	DPPH IC_{50} (μg mL^{-1})
1 (Gb-2a-glucoside)	13.67 ± 0.281	18.38 ± 0.112
2 (morelloflavone-glucoside)	15.35 ± 0.082	16.87 ± 0.337
3 (Gb-2a)	3.82 ± 0.350	27.20 ± 0.292
4 (volkensiflavone-glucoside)	2.61 ± 0.012	26.42 ± 0.006
5 (morelloflavone)	6.33 ± 0.016	21.26 ± 0.059
6 (volkensiflavone)	2.12 ± 0.272	33.92 ± 0.382
Ascorbic acid	17.91 ± 0.243	19.36 ± 0.036

Results are expressed as mean ± standard error of the mean (n = 3).

aglycone showed lower activity than the glucoside. This pattern was observed with all biflavonoids tested here, indicating that glycosylation enhances antioxidant activity. The higher IC_{50} values reported by Kuete and co-workers may be due to the higher DPPH concentration used in their assays.

Burda and Oleszek (2001) observed a relationship between certain structural features of flavonoids and antioxidant behaviour. Their studies demonstrated that a hydroxyl group in the *para* position on the B-ring is essential for activity and that this activity is enhanced by a second hydroxyl on the B-ring in the *ortho* position and a double bond between C2 and C3 on the C ring. These findings are consistent with aglycone activities observed in the current study. Overall, the data presented here demonstrates that *Allanblackia* seeds are an abundant source of highly active antioxidant phenolic components in common with seeds of the fruits of other tropical species including jabuticaba (*Myrciaria cauliflora*; Hacke et al., 2016) and guaraná (*Paullinia cupana*; Majhenič, Škerget, & Knez, 2007; Marques et al., 2016).

4. Conclusion

The comprehensive profile of soluble phenolics presented here confirms biflavonoids as the main phenolic compound class present and as major constituents of *A. floribunda* seeds. Due to their antioxidant activity and reported therapeutic properties, these compounds are of increasing interest to the pharmaceutical industry. With oil from *A. floribunda* seeds attracting attention from the food sector as a potential ingredient of margarine and other products (Cernansky, 2015), they could provide an excellent source of biflavonoids as a by-product.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

Ajibesin, K. K., Rene, N., Bala, D. N., & Essiett, U. A. (2008). Antimicrobial activities of the extracts and fractions of *Allanblackia floribunda*. *Biotechnology, 7*, 129–133.

Ayoola, G. A., Akpanika, G. A., Awobajo, F. O., Sofidiya, M. O., Osunkalu, V. O., Coker, H. A. B., et al. (2009). Anti-inflammatory properties of the fruits of *Allanblanckia floribunda* Oliv. (Guttiferae). *Botany Research International, 2*, 21–26.

Ayoola, G. A., Ipav, S. S., Sofidiya, M. O., Adepoju-Bello, A. A., Coker, H. A. B., & Odugbemi, T. O. (2008). Phytochemical screening and free radical scavenging activities of the fruits and leaves of *Allanblackia floribunda* Oliv (Guttiferae). *International Journal of Health Research, 1*, 87–93.

Azebaze, A. G. B., Menasria, F., Noumi, L. G., Nguemfo, E. L., Tchamfo, M. F., Nkengfack, A. E., et al. (2009). Xanthones from the seeds of *Allanblackia monticola* and their apoptotic and antiproliferative activities. *Planta Medica, 75*, 243–248.

Azebaze, A. G. B., Teinkela, J. E. M., Nguemfo, E. L., Valentin, A., Dongmo, A. B., & Vardamides, J. C. (2015). Antiplasmodial activity of some phenolic compounds from Cameroonians Allanblackia. *African Health Sciences, 15*, 835–840.

Benzie, I. F. F., & Strain, J. J. (1996). The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power": The FRAP assay. *Analytical Biochemistry, 239*, 70–76.

Betti, J. L. (2004). An ethnobotanical study of medicinal plants among the Baka pygmies in the Dja biosphere reserve, Cameroon. *African Study Monographs, 25*, 1–27.

Boudjeko, T., Ngomoyogoli, J. E. K., Woguia, A. L., & Yanou, N. N. (2013). Partial characterization, antioxidative properties and hypolipidemic effects of oilseed cake of *Allanblackia floribunda* and *Jatropha curcas*. *BMC Complementary and Alternative Medicine, 13*, 352–360.

Brand-Williams, W., Cuvelier, M. E., & Berset, C. (1995). Use of a free radical method to evaluate antioxidant activity. *LWT – Food Science and Technology, 28*, 25–30.

Brusotti, G., Papetti, A., Serra, M., Temporini, C., Marini, E., Orlandini, S., et al. (2016). *Allanblackia floribunda* Oliv.: An aphrodisiac plant with vasorelaxant properties. *Journal of Ethnopharmacology, 192*, 480–485.

Burda, S., & Oleszek, W. (2001). Antioxidant and antiradical activities of flavonoids. *Journal of Agricultural and Food Chemistry, 49*, 2774–2779.

Carrillo-Hormaza, L., Ramírez, A. M., Quintero-Ortiz, C., Cossio, M., Medina, S., Ferreres, F., et al. (2016). Comprehensive characterization and antioxidant activities of the main biflavonoids of *Garcinia madruno*: A novel tropical species for developing functional products. *Journal of Functional Foods, 27*, 503–516.

Cernansky, R. (2015). The African tree that could help replace palm oil. URL http://www.takepart.com/article/2015/12/18/african-tree-could-help-replace-palm-oil. Accessed 19.07.2016.

Cuyckens, F., & Claeys, M. (2004). Mass spectrometry in the structural analysis of flavonoids. *Journal of Mass Spectrometry, 39*, 1–15.

Fabre, N., Rustan, I., de Hoffmann, E., & Quetin-Leclercq, J. (2001). Determination of flavone, flavonol, and flavanone aglycones by negative ion liquid chromatography electrospray ion trap mass spectrometry. *Journal of the American Society for Mass Spectrometry, 12*, 707–715.

Fadeyi, S. A., Fadeyi, O. O., Adejumo, A. A., Okoro, C., & Myles, E. L. (2013). *In vitro* anticancer screening of 24 locally used Nigerian medicinal plants. *BMC Complementary and Alternative Medicine, 13*, 79–87.

Ferreres, F., Gil-Izquierdo, A., Andrade, P. B., Valentão, P., & Tomás-Barberán, F. A. (2007). Characterization of *C*-glycosyl flavones *O*-glycosylated by liquid chromatography-tandem mass spectrometry. *Journal of Chromatography A, 1161*, 214–223.

Fuller, R. W., Blunt, J. W., Boswell, J. L., Cardellina, J. H., & Boyd, M. R. (1999). Guttiferone F, the first prenylated benzophenone from *Allanblackia stuhlmannii*. *Journal of Natural Products, 62*, 130–132.

Hacke, A. C. M., Granato, D., Maciel, L. G., Weinert, P. L., do Prado-Silva, L., & Alvarenga, V. O. (2016). Jabuticaba (*Myrciaria cauliflora*) seeds: Chemical characterization and extraction of antioxidant and antimicrobial compounds. *Journal of Food Science, 81*, C2206–C2217.

Hauck, B., Gallagher, J. A., Morris, S. M., Leemans, D., & Winters, A. L. (2014). Soluble phenolic compounds in fresh and ensiled Orchard grass (*Dactylis glomerata* L.), a common species in permanent pastures with potential as a biomass feedstock. *Journal of Agricultural and Food Chemistry, 62*, 468–475.

Herbin, G. A., Jackson, B., Locksley, H. D., Scheinmann, F., & Wolstenholme, W. A. (1970). The biflavonoids of *Garcinia volkensii* (Guttiferae). *Phytochemistry, 9*, 221–226.

IUCN (International Union for Conservation of Nature, 2014). Allanblackia oil enters market in new margarine. URL https://www.iucn.org/news_homepage/news_by_date/?18536/Allanblackia-Oil-Enters-Market-in-New-Margarine. Accessed 19.07.2016.

Kayode, J. (2006). Conservation of indigenous medicinal botanicals in Ekiti State, Nigeria. *Journal of Zhejiang University Science B, 7*, 713–718.

Kuete, V., Azebaze, A. G. B., Mbaveng, A. T., Nguemfo, E. L., Tshikalange, E. T., Chalard, P., et al. (2011). Antioxidant, antitumor and antimicrobial activities of the crude extract and compounds of the root bark of *Allanblackia floribunda*. *Pharmaceutical Biology, 49*, 57–65.

Locksley, H. D., & Murray, I. G. (1971). Extractives from Guttiferae. Part XIX. The isolation and structure of two benzophenones, six xanthones and two biflavonoids from the heartwood of *Allanblackia floribunda* Oliver. *Journal of the Chemical Society C: Organic*, 1332–1340.

Mabry, T. J., Markham, K. R., & Thomas, M. B. (1970). *The systematic identification of flavonoids*. New York: Springer Verlag.

Majhenič, L., Škerget, M., & Knez, Ž. (2007). Antioxidant and antimicrobial activity of guarana seed extracts. *Food Chemistry, 104*, 1258–1268.

Marques, L. L. M., Panizzon, G. P., Aguiar, B. A. A., Simionato, A. S., Cardozo-Filho, L., Andrade, G., et al. (2016). Guaraná (*Paullinia cupana*) seeds: Selective supercritical extraction of phenolic compounds. *Food Chemistry, 212*, 703–711.

Nkengfack, A. E., Azebaze, G. A., Vardamides, J. C., Fomum, Z. T., & van Heerden, F. R. (2002). A prenylated xanthone from *Allanblackia floribunda*. *Phytochemistry, 60*, 381–384.

Olowokudejo, J. D., Kadiri, A. B., & Travih, V. A. (2008). An ethnobotanical survey of herbal markets and medicinal plants in Lagos state of Nigeria. *Ethnobotanical Leaflets, 12*, 851–865.

Orwa, C. & Munjuga, M. (2007). *Allanblackia floribunda* Oliv. Internet Record from PROTA4U. van der Vossen, H.A.M. & Mkamilo, G.S. (editors). PROTA (Plant Resources of Tropical Africa/Ressources végétales de l'Afrique tropicale), Wageningen, Netherlands. URL http://www.prota4u.org/search.asp or http://uses.plantnet-project.org/en/Allanblackia_floribunda_(PROTA). Accessed 19.07.2016.

Orwa C., Mutua A., Kindt R., Jamnadass R. & Anthony S. (2009). Agroforestree Database: a tree reference and selection guide version 4.0. URL http://www.worldagroforestry.org/treedb/AFTPDFS/Allanblackia_floribunda.PDF. Accessed 19.07.2016.

Stark, T. D., Lösch, S., Wakamatsu, J., Balemba, O. B., Frank, O., & Hofmann, T. (2015). UPLC-ESI-TOF MS-based metabolite profiling of the antioxidative food supplement *Garcinia buchananii*. *Journal of Agricultural and Food Chemistry, 63*, 7169–7179.

Vukics, V., & Guttman, A. (2010). Structural characterization of flavonoid glycosides by multi-stage mass spectrometry. *Mass Spectrometry Reviews, 29*, 1–16.

Wilfred, S., Adubofuor, J., & Oldham, J. H. (2010). Optimum conditions for expression of oil from *Allanblackia floribunda* seeds and assessing the quality and stability of pressed and solvent extracted oil. *African Journal of Food Science, 4*, 563–570.

Yang, H., Figueroa, M., To, S., Baggett, S., Jiang, B., Basile, M. J., et al. (2010). Benzophenones and biflavonoids from *Garcinia livingstonei* fruits. *Journal of Agricultural and Food Chemistry, 58*, 4749–4755.