Research article

Evaluation of chemical composition, *in vitro* antioxidant, and antidiabetic activities of solvent extracts of *Irvingia gabonensis* leaves

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ABSTRACT

Irvingia gabonensis commonly referred to as wild mango or ogbono is a tropical plant with both nutritional and medicinal uses. The present study was designed to evaluate the chemical composition, *in vitro* antioxidant activity, and inhibitory activity of carbohydrate hydrolyzing enzymes related to diabetes by different extracts of the plant. From the results of the study, Total Phenolic Content (TPC) was highest in the aqueous and ethanol extracts (367.30 ± 00 mg/100g GAE) compared to the chloroform and n-hexane extracts whereas the Total Flavonoid Content (TFC) was highest (230.69 ± 0.18 mg/100g QE) in the ethanol extract. Analysis of the *in vitro* antioxidant activity showed that the ethanol extract also possessed the highest 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity (IC_{50}: 21.42 ± 0.05 µg/ml) and hydroxyl radical scavenging activity (81.43 ± 0.11%) compared to other solvent extracts. The aqueous extract had the highest (23.91 ± 0.04 mM Fe++ equivalent) ferric antioxidant reducing power (FRAP). However, the antioxidant activity of the extracts was significantly lower than that of the reference compounds used for the study (butylated hydroxytoluene and Gallic acid). *In vitro* antidiabetic activity of the extracts was measured based on inhibition of α-amylase and α-glucosidase. The aqueous extract had the highest α-amylase and α-glucosidase inhibitory activity followed by the ethanol extract compared to the chloroform and n-hexane extracts. The inhibitory activity of the aqueous extract against both enzymes was higher compared to the reference compound Acarbose. Gas Chromatography-Mass Spectrometry analysis of the extracts revealed the presence of chemical constituents including fatty acids, vitamin, phytosterols, aromatic compounds, glycosides. The interaction of these compounds with α-amylase and α-glucosidase was evaluated *in silico* by molecular docking. Phytosterols namely, campesterol, stimasterol and γ-sitosterol had the best binding affinities to α-amylase and α-glucosidase. In conclusion, the results of this study revealed that the aqueous and ethanol extracts of *Irvingia gabonensis* had the highest phenolic content, antioxidant activity, and *in vitro* antidiabetic activity. These results offer a scientific explanation for the mode of preparation and traditional use of the plant in the treatment of diabetes.

1. Introduction

Diabetes mellitus (DM) is a leading health problem in low and middle-income countries (Nguelefack et al., 2020). In 2019 DM caused 4.3 million deaths worldwide. Current statistics reveal that 463 million adults are currently diabetic and the number of affected persons is expected to double by 2045 (Nguelefack et al., 2020). The disease is therefore a public emergency. DM is characterized by a chronic disorder in the metabolism of carbohydrates, proteins, and lipids resulting from a deficiency in insulin production (type 1 diabetes) or insulin resistance (type 2 diabetes) leading to chronic hyperglycemia (Jemaa et al., 2017; Kifle et al., 2021; Atanu et al., 2018). Type 2 diabetes which is predominant in adults appears to be more common than type 1 which has its onset in adolescence. The common denominator in both types of diabetes is hyperglycemia which must be routinely monitored. The World Health Organization (WHO) reports that DM is responsible for significant economic loss accounted for by medical costs paid by patients, reduction of man-hours, and possible loss of manpower as a result of ill-health (Quan et al., 2019). DM often leads to complications such nephropathy, ulcer, cardiovascular disease, retinopathy, and nerve damage. Current treatment options available for DM include the use of oral hypoglycemic drugs, controlled exercise, diet modification, use of natural products from plants, and insulin therapy. However, due to the rising cases of DM, there is a need for new drugs which have better efficacy and are less toxic.

Carbohydrates in form of starch and simple sugars constitute a major part of the human diet. The recommended daily intake of carbohydrates is 40–45% which is sufficient to fulfill the energy needs of the human body. Breakdown of the starch produces monosaccharides which are further catabolized to release energy or stored as glycogen (Majeed et al., 2020; Avwioroko et al., 2019). In addition, the breakdown of starch after a meal leads to an increase in postprandial glucose concentration leading to hyperglycemia. Diabetics control hyperglycemia by engaging in glycemic control through fasting however, the effectiveness of this strategy is limited (Nguelefack et al., 2020). A potent approach to checking postprandial hyperglycemia in diabetics is by slowing the digestion of carbohydrates by inhibiting pancreatic α-amylase and intestinal α-glucosidase. Current prescription drugs for inhibition of α-glucosidase and α-amylase include such as acarbose, miglitol, and voglibose however, there are reported cases of adverse effects (Alqahtani et al., 2019). Chronic hyperglycemia is positively correlated to increased production of reactive oxygen species (ROS) leading to oxidative stress. Consequently, ROS oxidizes cellular components leading to impairment of cell function. Indeed an impairment of redox status has been reported in diabetic patients while antioxidants have been shown to reverse the complication of diabetes (Misbah et al., 2013).

Medicinal plants are commonly used in low-income countries for the treatment of human diseases. Phytochemicals from plants are believed to be safe and effective with the added advantage of being affordable (Kifle et al., 2021). To date, more than 200 pure compounds with antihyperglycemic activity have been isolated from plants (Misbah et al., 2013).

Irvingia gabonensis, is an African plant commonly referred to as 'bush mango'. It is harnessed for both medicinal and nutritional benefits (Mateus-Reguengo et al., 2020). Traditionally the leaves of the plant is used for the treatment of diabetes while the seeds are used for 'African soup' and is believed to have antidiabetic effects. Based on available experimental evidence, it is proven that the leaves and stem extracts of *Irvingia* regulate blood glucose and lipid profile (Sulaimon et al., 2015). In a clinical study, seeds of *Irvingia gabonensis* were shown to cause a reduction in plasma lipids and an increase in HDL-cholesterol (Adamson et al., 1990). Similar results were obtained in a randomized double-blind, placebo-controlled clinical trial which revealed that patients fed with *Irvingia gabonensis* for 90 days had reduced waist circumference, glucose, and blood lipids (Méndez-Del Villar et al., 2018). In a report by Omoruyi & Adamson (1993), fiber extract from *Irvingia gabonensis* was shown to elevate the activities of hepatic glycolytic enzymes with a concomitant depletion of glycogen. Several studies have affirmed the effectiveness of extracts from *Irvingia gabonensis* against toxicity from various chemical agents (Gbadegesin et al., 2014; Olorundare et al., 2020a, 2020b).

Therefore, the present study was designed to evaluate the chemical composition, *in vitro* antioxidant activity, and effect of different solvent extracts from leaves of *Irvingia gabonensis* on glucose metabolizing enzymes linked to diabetes mellitus.

2. Materials and methods

2.1. Chemicals

α-amylase, α-glucosidase, 2,2-diphenyl-1-picrylhydrazyl (DPPH), 1,10 phenanthroline, dinitrosalicylic acid, p-nitrophenyl-α-D-glycopyranoside, gallic acid, quercetin, and butylated hydroxytoluene were purchased from Sigma Aldrich chemical company (St. Louis, MO, USA). Ethanol, chloroform, and n-hexane were products of British Drug House (BDH). Every other chemical used for the study was of analytical grade purchased from Fisher Scientific (UK).

2.2. Collection and identification of the plant

Leaves of *Irvingia gabonensis* were collected from Egbe village in Kogi State, Nigeria. The plant was identified and authenticated at the Department of Plant Science and Biotechnology, Kogi State University, Anyigba.

2.3. Preparation of plant material

The leaves were washed with water and air-dried to constant weight at room temperature. Dried leaves were pulverized with the aid of an electric blender. The pulverized leaves were soaked (17.3 % w/v) separately in water, ethanol, chloroform, and n-hexane for two days. The suspension was filtered and the filtrate was concentrated in a water bath.

2.4. Test for total phenolic content

Total phenolic content (TPC) was measured using the Folin-Ciocalteu method described by Das et al. (2019). Dilutions of plant extracts (50 μl) were mixed with 150 μl of Folin-Ciocalteu reagent followed by the addition of 600 μl of 15% Na_2CO_3 solution and incubated for 2 h. Absorbance was taken at 760 nm. A standard calibration plot was prepared using gallic acid and the total phenolic content of extracts was expressed as mg Gallic acid equivalents (GAE)/100 g of extract (Samatha et al., 2012).

2.5. Test for total flavonoid content

Total flavonoid content (TFC) was determined by the aluminum chloride method described by Das et al. (2019). Plant extracts were diluted and 1 mL extract was added to 4 mL of distilled water in a volumetric flask followed by the addition of 0.3 mL of 5% $NaNO_2$. The reaction mixture was allowed to stand for 5 min, and then 0.3 mL of 10% $AlCl_3$ was added. The reaction was incubated for 1 min then 2 mL of 1 M NaOH was added and the total volume was made up to 10 mL with distilled water. Absorbance was read at 510 nm. A standard calibration plot was prepared using Quercetin and total flavonoid content of extracts was expressed as mg Quercetin equivalents (QE)/100 g of extract (Samatha et al., 2012).

2.6. 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity

The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity of plant extracts was determined based on the method reported by Shah et al. (2017). An aliquot 0.3 mL of various concentrations of plant extract ranging between 10–50 μg/mL were mixed with 2.7 ml of DPPH (6×10^{-5} M) in methanol and left in the dark for 1 h. Absorbance of the reaction mixture was taken at 512 nm. Butylated hydroxytoluene (BHT) was used standard antioxidant compound. The radical scavenging activity was calculated according to Equation 1 below:

$$\% \text{ DPPH radical scavenging activity} = \frac{\text{ABScontrol} - \text{ABSsample}}{\text{ABScontrol}} \text{X } 100$$

(1)

where ABScontrol is the absorbance value of blank and ABSsample is the absorbance value of extract or standard.

The potency of the biological sample (plant extracts) and standard (BHT) was determined based on the concentration of the sample at which 50% radical inhibition (IC_{50}) was observed as extrapolated from a linear regression analysis of percentage inhibition plotted against sample concentration.

2.6.1. Ferric reducing antioxidant power (FRAP)

Ferric Reducing Antioxidant Power (FRAP) of the extracts was determined using the Benzie and Strain method (1996). Briefly, acetate buffer (Reagent A) was prepared by dissolving 3.1g of sodium acetate trihydrate in 16 ml of glacial acetic acid pH 3.6. Reagent B was prepared from a combination of TPTZ (2, 4, 6-tripyridyl-s- triazine) and 10 mM in 40 mM HCl. Reagent C was a solution of 20 mM $FeCl_3.6H_2O$. FRAP reagent was constituted by mixing Reagents A, B, and C in a ratio of 10:1:1. FRAP reagent (3.6 ml) was added to distilled water (0.4 ml) and mixed with 80 ml of plant extract. The reaction was incubated at 37 °C for 10

min. FRAP value of the extracts was extrapolated from a standard FeSO$_4$.7H$_2$O and expressed as mM Fe++ equivalents (Noreen et al., 2017).

2.7. Hydroxyl radical scavenging activity

The hydroxyl radical scavenging activity of extracts from *Irvingia gabonensis* was determined according to the method described by Kim et al. (2020). In order to generate hydroxyl radical 1.0 mL of 1,10-phenanthroline was mixed with 2.0 mL of 0.2 M sodium phosphate buffer (pH 7.4) and 1.0 mL of 0.75 mM FeSO$_4$ and 1.0 mL of H$_2$O$_2$. The mixture was incubated with 1 ml of sample for 10 min at 37 °C. Gallic acid was used as standard. Absorbance was measured at 510 nm and the hydroxyl radical scavenging activity was calculated according to Equation 2 below:

$$\% \text{ OH radical scavenging activity} = \frac{\text{ABSsample}}{\text{ABScontrol}} \text{ X } 100 \qquad (2)$$

where ABSsample is the absorbance of the extract or standard and ABScontrol is the absorbance of the blank.

2.8. α-Amylase inhibition assay

α-Amylase inhibition assay was carried out according to the dinitrosalicylic acid method as described by Oboh et al. (2014). Briefly, 500 μL various concentrations of the extracts and 500 μL of 0.5 mg/ml pancreatic α-amylase (EC 3.2.1.1) in 0.02 M sodium phosphate buffer (pH 6.9 with 0.006 M NaCl) were mixed. Starch, 1% (500 μL) was added and the reaction mixture was incubated at 25 °C for 10 min. Thereafter, the reaction was stopped by the addition of 1.0 mL of dinitrosalicylic acid color reagent. The mixture was boiled for 5 min followed by a cooling step and the volume was made up to 10 ml with distilled water. Absorbance was read at 540 nm and IC$_{50}$ (the extract concentration inhibiting 50% of the α-amylase activity) was calculated.

2.9. α-glucosidase inhibition assay

α-Glucosidase inhibition assay was carried out based on the protocol reported by Oboh et al. (2014). An aliquot 100 μL of α-glucosidase solution (1.0 U/ml; in 0.1 *M phosphate* buffer pH 6.9) was adapted to a temperature of 25 °C for 10 min followed by the addition of 50 μL of 5 mM p-nitrophenyl-α-D-glucopyranoside solution in the presence of various concentration of extract. The reaction mixture was incubated for 5 min at 25 °C before measuring absorbance at 405 nm and IC$_{50}$ (the extract concentration inhibiting 50% of the α-amylase activity) was calculated.

2.10. Gas chromatography-mass spectrometry (GC–MS) analysis

GC-MS analysis of extracts of *Irvingia gabonensis* was performed on an Agilent 7890 coupled to JeolAccuTOF GCV, USA equipped with an HP5MS fused silica capillary column (length—30m, thickness— 0.25μm, internal diameter—25mm). Helium was used as the carrier gas at a flow rate of 1 mL/min and an ionization volt of 70eV. The compounds present in the plant extracts were identified based on comparison of their retention time (min), peak area, peak height, and mass spectral patterns with data on compounds in the database of National Institute of Standards and Technology (NIST).

2.11. In silico experiments

Molecular docking experiments were carried out to probe the interaction of ligands with α-amylase and α-glucosidase. Docking studies was performed using the AutoDock4.2 incorporated in the Pyrx software. Three dimensional structures of α-amylase (PDB ID: 1OSE) and α-glucosidase (PDB ID: 3TOP) were downloaded from the RSCB Protein Data Bank (PDB). The structures were cleaned by removing water molecules, ligands, and other co-crystallized molecules. A grid box with dimensions 26.3 × 25.0 × 25.8 for α-amylase and 25.0 × 25.0 × 25.0 for α-glucosidase was assigned prior to docking. Structures of the docked ligands were visualized using PyMol and Discovery studio 5.0.

2.12. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics version 20. Results were presented as mean ± SEM of four determinations. The differences between samples were analyzed by one-way analysis of variance (ANOVA). Duncan's POST-HOC test was performed to determine statistical significance at p-value of 0.05.

3. Results and discussion

3.1. Phenolic and flavonoid content of Irvingia gabonensis

Four solvent extracts namely: aqueous, ethanol, chloroform and n-hexane were used for this study. The total phenolic and flavonoid contents are as shown in Figure 1. Total phenolic contents (TPC) of the aqueous and ethanol extracts were significantly higher than TPC of the chloroform and n-hexane extracts (p < 0.05). The TPC are in the following order Aqueous = Ethanol (367.30 ± 00 mg GAE/100g) > Chloroform (57.70 ± 0.14 mg GAE/100g) > n-hexane (31.45 ± 0.21 mg GAE/100g). Similarly, the total flavonoid contents (TFC) of four extracts were statistically different (p < 0.05). The TFC of the extracts is a follows: Ethanol (230.69 ± 0.18 mg QE/100g) > aqueous (121.08 ± 0.36 mg QE/100g) > n-hexane (108.00 ± 0.36 mg QE/100g) > chloroform (26.62 ± 0.36 mg QE/100g). The most important variable in the extraction process in this study is the choice of solvent. The different solvent extracts demonstrated variable phenolic and flavonoid contents which reflect their ability to selectively solubilize certain phytochemicals. The high levels of phenolic content of the aqueous and ethanol extracts may suggest that they are rich sources of nutraceuticals. Moreover, ethanol and water are safe for consumption and inexpensive solvents that are most commonly used for extracting plants for herbal medicines. Our results are in agreement with earlier studies that confirmed the presence of Phenolic and flavonoid compounds in the leaves of *Irvingia gabonensis* (Mgbemena et al., 2019; Idume and Barney, 2018; Ojemekele et al., 2017; Ewere et al., 2016).

3.2. Antioxidant activity of solvent extracts of Irvingia gabonensis

In vitro antioxidant activity was measured based on the capacity of the different extracts to scavenge DPPH radical, ferric reducing antioxidant power (FRAP), and hydroxyl radical scavenging activity. The results of the *in vitro* antioxidant activity of the solvent extracts are presented in Table 1. All extracts showed antioxidant activity. The results of the study reveal that the ethanol extract had the strongest DPPH radical inhibitory activity which was comparable to butylated hydroxytoluene (BHT) (p > 0.05). However, the DPPH radical inhibitory activity of the ethanol extract (IC$_{50}$: 21.42 ± 0.05 μg/ml) was significantly higher (p < 0.05) than that of the aqueous (IC$_{50}$: 30.74 ± 0.21 μg/ml), chloroform (IC$_{50}$: 36.62 ± 0.01 μg/ml), and n-hexane (IC$_{50}$: 31.41 ± 0.02 μg/ml) extracts. FRAP value expressed as concentration of mM Fe++ equivalents in solution was highest for the aqueous extracts (23.91 ± 0.04 mM Fe++ equivalent) but was significantly lower (p < 0.05) than the value for gallic acid (28.08 ± 0.01 mM Fe++ equivalent). The n-hexane extract had the least FRAP value of 11.57 ± 0.02 mM Fe++ equivalent. Analysis of the hydroxyl radical inhibitory activity of the extracts revealed that the ethanol (81.43 ± 0.11%) and chloroform extracts (69.66 ± 0.53%) had the strongest inhibitory activity and were significantly higher (p < 0.05) than activities recorded for the aqueous and n-hexane extracts (23.02 ± 0.32 and 23.77 ± 0.32% respectively). Concerning the high phenolic contents of the aqueous and ethanol extracts, this pattern of result is
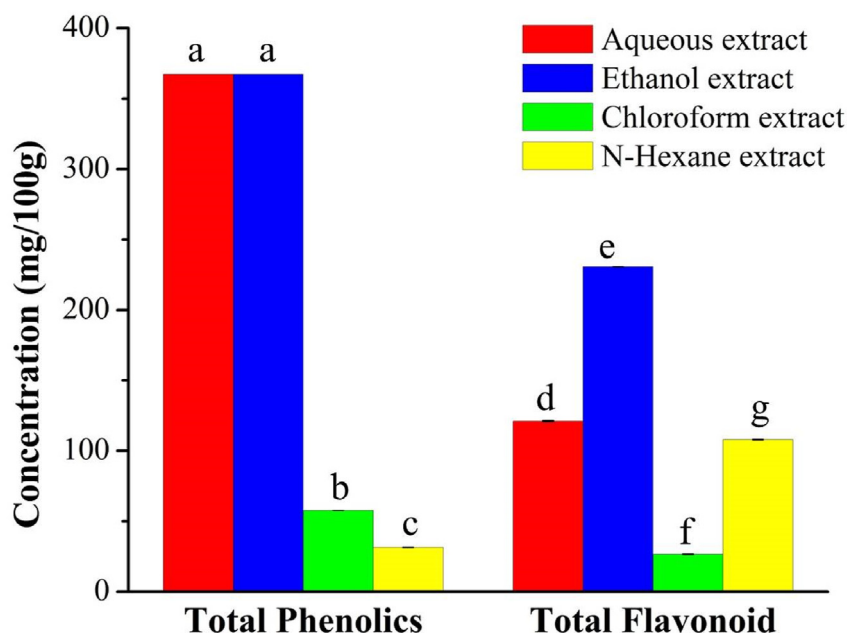
Figure 1. Total phenolic and flavonoid content of solvent extracts of *Irvingia gabonensis*. Results are presented as mean ± SEM of four determinations. Bars for the same parameter with different superscripts are statistically significantly different (p < 0.05).

Table 1. *In vitro* antioxidant activity of solvent extracts of *Irvingia gabonensis*.

Sample	IC$_{50}$ Inhibition of DPPH radical (μg/ml)	FRAP value (mM Fe++ equivalent)	Hydroxyl radical inhibition (%)
Aqueous extract	30.74 ± 0.21[a]	23.91 ± 0.04[a]	23.02 ± 0.32[a]
Ethanol extract	21.42 ± 0.05[b]	22.25 ± 0.02[b]	81.43 ± 0.11[b]
Chloroform extract	36.62 ± 0.01[c]	22.43 ± 0.04[b]	69.66 ± 0.53[c]
N-Hexane extract	31.41 ± 0.02[d]	11.57 ± 0.02[c]	23.77 ± 0.32[a]
Reference	BHT: 21.73 ± 0.06[b]	GA: 28.08 ± 0.01[d]	GA: 100.00 ± 00[d]

Values are presented as mean ± SEM of four determinations. Values in the same column with different superscripts are statistically significantly different (p < 0.05). BHT: Butylated hydroxytoluene; GA: Gallic acid.

expected. Phenolic compounds are known to be strong antioxidants. Their antioxidant activity is dependent on reducing potential which allows them to donate protons, scavenge oxygen radical species as well as chelate metals (Jemaa et al., 2017). By these mechanisms, they can neutralize free radicals (Quan et al., 2019). The results of this work mirror those of Ojemekele et al. (2017) and Ewere et al. (2016).

3.3. In vitro antidiabetic activity

Management of blood glucose is one of the effective strategies for combating diabetes mellitus. Postprandial blood glucose level rises due to the activity of carbohydrate hydrolyzing enzymes: α-amylase and α-glucosidase. Inhibitors of these enzymes are currently used as oral hypoglycemic drugs for the control of hyperglycemia, especially in patients with type-2 diabetes mellitus. The inhibitors delay the release of monosaccharides from polysaccharides present in food (Oboh et al., 2012; Avwioroko et al., 2020). In the present study the effect of extracts of *Irvingia gabonensis* on the hydrolytic activity of amylase and α-glucosidase was tested. Figure 2 shows the α-amylase and α-glucosidase inhibitory activities of extracts of *Irvingia gabonensis*. A comparison of the inhibitory activities of the extracts against α-amylase and α-glucosidase based on the measured IC$_{50}$ revealed that all solvents extracts were statistically different. The order of inhibition α-amylase was aqueous extracts > ethanol extracts > acarbose (reference) > n-hexane extracts and

chloroform extracts. The observed inhibition for α-glucosidase was by the order aqueous extracts > ethanol extracts > chloroform extracts > acarbose (reference) > n-hexane extracts. In general, the IC$_{50}$ values for α-amylase were higher than for α-glucosidase. The extracts exhibited the protein target preference of an ideal oral hypoglycemic drug. An ideal oral hypoglycemic drug has milder inhibitory activity on amylase than α-glucosidase. Complete inhibition of amylase is counterproductive and leads to the accumulation of undigested starch which promotes the growth of intestinal microflora causing disorders such as diarrhea, abdominal pain, and flatulence (Cedó et al., 2019; Paudel et al., 2018; Avwioroko et al., 2019; Atanu et al., 2021).

Plants rich in phenolic compounds are known for their ability to inhibit amylase and α-glucosidase thereby reducing postprandial blood glucose level. Chronic hyperglycemia which is common in DM is responsible for diabetic complications such as accumulation of glycated end products, nephropathy, and neuropathy, cardiovascular disease, and atherosclerosis (Olennikov et al., 2016). In this study, the aqueous and ethanol extracts with the highest phenolic contents also had the strongest inhibitory activity against the two enzymes. This suggests that the phenolic compounds have a combined positive antidiabetic effect.

Although experimental evidence is abundant on the pharmacological effect of seeds of *Irvingia gabonensis* on diabetes, evidence of antidiabetic activity of the leaves are relatively scarce. Sulaimon et al. (2015) revealed that extracts of *Irvingia gabonensis* had a positive effect on blood sugar, body weight, and haematological parameters of diabetic rats.

3.4. Bioactive compounds identified by GC-MS fingerprinting

Figures 3 and 4 depict the chromatograms for the gas chromatography analysis for the aqueous and ethanol extracts respectively. Figures 3 and 4 show the mass spectrometry data for the 34 compounds identified in the aqueous and ethanol extracts. The compounds belong to different classes including fatty acids, sterols, glycosides, and esters. Some of the compounds found in high concentration in the aqueous extracts were Propanamide N,N-dimethyl-, 4H-Pyran-4-one 2,3-dihydro-3,5-dihydroxy-6-methyl-, catechol, 3-Methyl-2-furoic acid, 1,2,3-Benzenetriol, and Carbonic acid, 2-ethylhexyl pentadecyl ester (Table 2). The ethanol extract on the other hand possessed high concentrations of n-Hexadecanoic acid [1,2,5]Oxadiazolo[3,4-b][1,4]diazocine-5,7(4H, 6H)-dione, 8,9-dihydro,
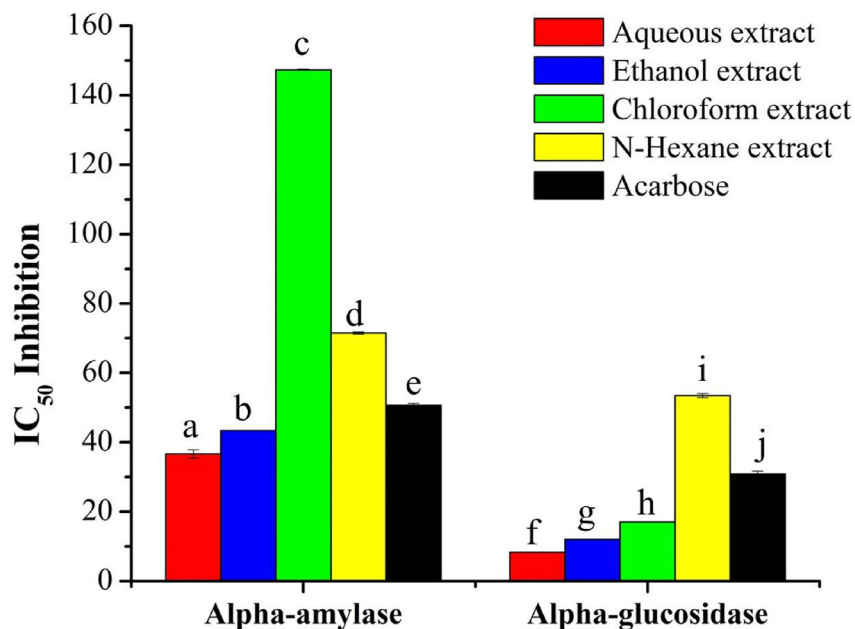
Figure 2. Inhibition of α-amylase and α-glucosidase by solvent extracts of *Irvingia gabonensis*. Results are presented as mean ± SEM of four determinations. Bars for the same parameter with different superscripts are statistically significantly different (p < 0.05).
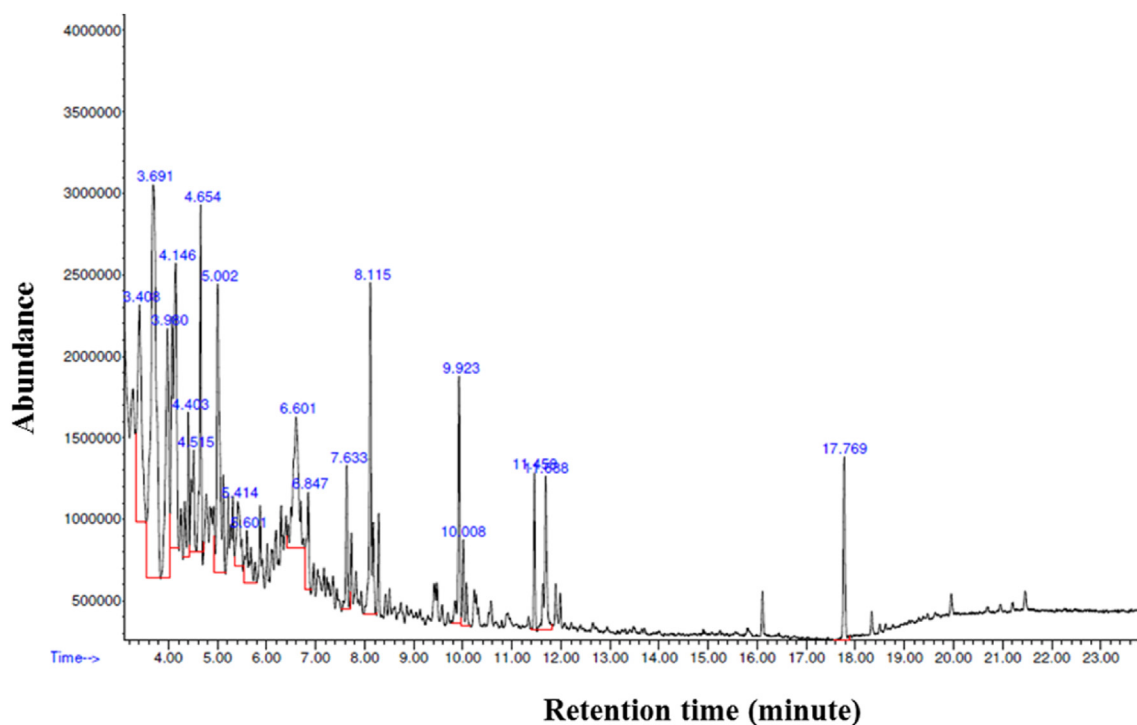

Figure 3. Chromatogram of gas chromatography analysis of aqueous extracts of *Irvingia gabonensis*.

Cyclohexane, 1-ethenyl-1-methyl-2, 4-bis(1-methylethenyl)- [1S-(1. alpha.,2. beta.,4. beta.)]-, oleic acid and ethyl oleate (Table 2). Several plants possessing some of these phytochemicals have been reported to possess different pharmacological benefits such anticancer, antiin-flammatory, antioxidant, antidiabetic and hypolipidemic effects (Paudel et al., 2018; Naz et al., 2020; Batiha et al., 2020; Nokhala et al., 2020; Al-Nemari et al., 2020; Anigboro et al., 2021). Therefore, the presence of these compounds in extracts of *Irvingia gabonensis* may reflect the variety of pharmacological benefits attributed to the plant.

3.5. Analysis of molecular interaction

Docking studies were performed to predict the strength and type of interaction between the compounds identified by GC-MS and target proteins: α-amylase and α-glucosidase (Table 3). All compounds showed binding affinity to α-amylase and α-glucosidase. Stigmasterol showed the strongest binding affinity to both α-amylase (9.8 kcal/mol) and α-glucosidase (9.7 kcal/mol). Structurally related compounds of the phytosterol family namely campsterol and γ-Sitosterol also showed good
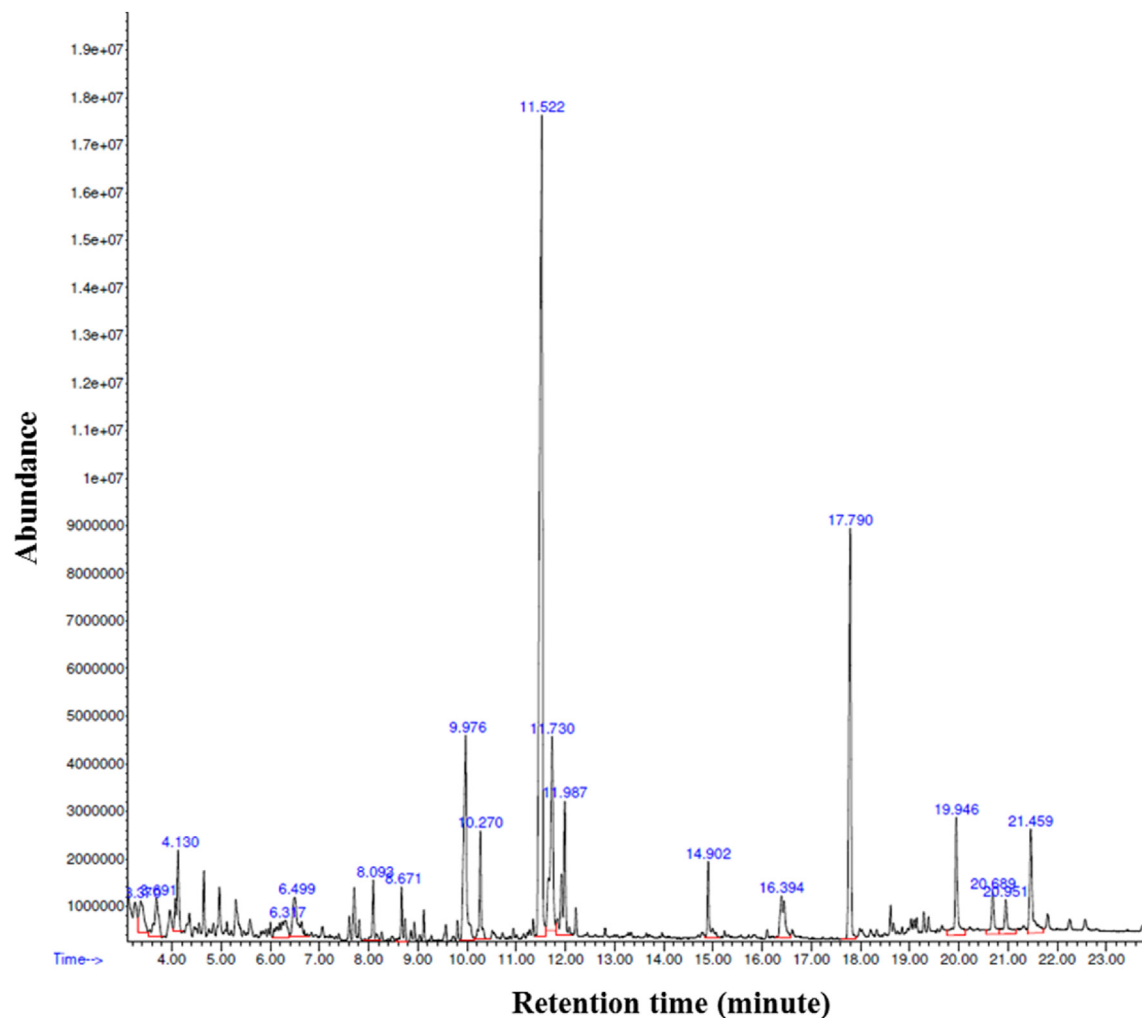
Figure 4. Chromatogram of gas chromatography analysis of ethanol extracts of *Irvingia gabonensis*.

Table 2. Chemical composition of solvent extracts *Irvingia gabonensis*.

S.No.	Retention time (min)	PubChem ID	Compound	Area %	
				Aqueous	Ethanol
1	3.370	77487	Butanedioic acid, monomethyl ester		2.04
2	3.408	12965	Propanamide, N,N-dimethyl-	8.25	-
3	3.691	119838	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl-	19.68	2.33
4	3.980	289	Catechol	7.43	-
5	4.146	78127	3-Methyl-2-furoic acid	10.76	-
6	4.403	785	Hydroquinone	2.47	-
7	4.515	222285	Erythritol	2.38	-
8	4.654	12570	Phenol, 2-propyl-	5.01	-
9	5.002	1057	1,2,3-Benzenetriol	8.27	-
10	5.414	536755	1-Nitro-2-acetamido-1,2-dideoxy-d-glucitol	2.19	-
11	5.601	5353029	3-Cyclopentylpropionic acid, oct-3-en-2-yl ester	2.13	-
12	6.317	14035098	Butyrovanillone	-	2.03
13	6.499	14512	4(1H)-Pyrimidinone, 6-hydroxy-	-	2.78
14	6.601	91693131	Carbonic acid, 2-ethylhexyl pentadecyl ester	6.79	-
15	6.847	139926	Benzene, 1-(1,1-dimethylethoxy)-4-methyl-	1.87	-
16	7.633		Benzeneacetic acid, 4-hydroxy-3-methoxy-, methyl ester	2.18	-
17	8.115	85214	6-Hydroxy-4,4,7a-trimethyl-5,6,7,7 a-tetrahydrobenzofuran-2(4H)-one	6.62	-
18	8.671	10446	Neophytadiene	-	1.62
19	9.976	985	n-Hexadecanoic acid	-	8.46

Table 2 (*continued*)

S.No.	Retention time (min)	PubChem ID	Compound	Area %	
				Aqueous	Ethanol
20	10.008	6818	1,2-Benzenedicarboxylic acid, butyl 2-ethylhexyl ester	1.70	-
21	10.270	12366	Hexadecanoic acid, ethyl ester	-	2.64
22	11.458	5280435	Phytol	1.93	-
23	11.522	136654713	[1,2,5]Oxadiazolo[3,4-b][1,4]diazocine-5,7(4H,6H)-dione, 8,9-dihydro	-	31.83
24	11.688	5282761	cis-Vaccenic acid	3.40	-
25	11.730	445639	Oleic Acid	-	7.93
26	11.987	5363269	Ethyl Oleate	-	5.23
27	14.902	123409	Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester	-	2.12
28	16.394	5364643	cis-9-Hexadecenal	-	2.68
29	17.769	638072	Squalene	3.05	-
30	17.790	9859094	Cyclohexane, 1-ethenyl-1-methyl-2, 4-bis(1-methylethenyl)-, [1S-(1.alpha.,2.beta.,4.beta.)]-	-	12.33
31	19.946	2116	DL-alpha-Tocopherol	-	4.16
32	20.689	173183	Campesterol	-	1.81
33	20.951	5280794	Stigmasterol	-	1.64
34	21.459	457801	gamma-Sitosterol	-	4.20

Table 3. Molecular docking scores of chemical constituents of *Irvingia gabonensis* to protein targets.

| S.No.	PubChem ID	Compound	Docking score (kcal/mol)	
			α-amylase	α-glucosidase
1	77487	Butanedioic acid, monomethyl ester	-4.3	-5.2
2	12965	Propanamide, N,N-dimethyl-	-3.6	-4.7
3	119838	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl-	-5.0	-6.2
4	289	Catechol	-5.0	-5.7
5	78127	3-Methyl-2-furoic acid	-5.1	-5.8
6	785	Hydroquinone	-4.8	-5.5
7	222285	Erythritol	-4.0	-4.6
8	12570	Phenol, 2-propyl-	-5.6	-6.4
9	1057	1,2,3-Benzenetriol	-5.1	-6.2
10	536755	1-Nitro-2-acetamido-1,2-dideoxy-d-glucitol	-5.6	-6.1
11	5353029	3-Cyclopentylpropionic acid, oct-3-en-2-yl ester	-7.0	-6.5
12	14035098	Butyrovanillone	-6.4	-7.0
13	14512	4(1H)-Pyrimidinone, 6-hydroxy-	-4.7	-5.6
14	91693131	Carbonic acid, 2-ethylhexyl pentadecyl ester	-5.7	-6.4
15	139926	Benzene, 1-(1,1-dimethylethoxy)-4-methyl-	-5.9	-6.5
16	14334	Benzeneacetic acid, 4-hydroxy-3-methoxy-, methyl ester	-7.3	-5.8
17	85214	6-Hydroxy-4,4,7a-trimethyl-5,6,7,7 a-tetrahydrobenzofuran-2(4H)-one	-5.9	-6.7
18	10446	Neophytadiene	-6.2	-6.4
19	985	n-Hexadecanoic acid	-5.3	-6.1
20	6818	1,2-Benzenedicarboxylic acid, butyl 2-ethylhexyl ester	-6.8	-7.4
21	12366	Hexadecanoic acid, ethyl ester	-5.8	-5.9
22	5280435	Phytol	-6.3	-6.4
23	136654713	[1,2,5]Oxadiazolo[3,4-b][1,4]diazocine-5,7(4H,6H)-dione, 8,9-dihydro	-6.4	-7.2
24	5282761	cis-Vaccenic acid	-5.6	-6.4
25	445639	Oleic Acid	-6.1	-6.5
26	5363269	Ethyl Oleate	-5.7	-5.9
27	123409	Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester	-5.6	-5.8
28	5364643	cis-9-Hexadecenal	-5.3	-6.0
29	638072	Squalene	-7.3	-7.6
30	9859094	Cyclohexane, 1-ethenyl-1-methyl-2, 4-bis(1-methylethenyl)-, [1S-(1.alpha.,2.beta.,4.beta.)]-	-7.0	-6.8
31	2116	DL-alpha-Tocopherol	-8.0	-7.8
32	173183	Campesterol	-9.5	-9.5
33	5280794	Stigmasterol	-9.8	-9.7
34	457801	γ-Sitosterol	-9.5	-9.6
35	41774	Acarbose	-7.9	-7.9
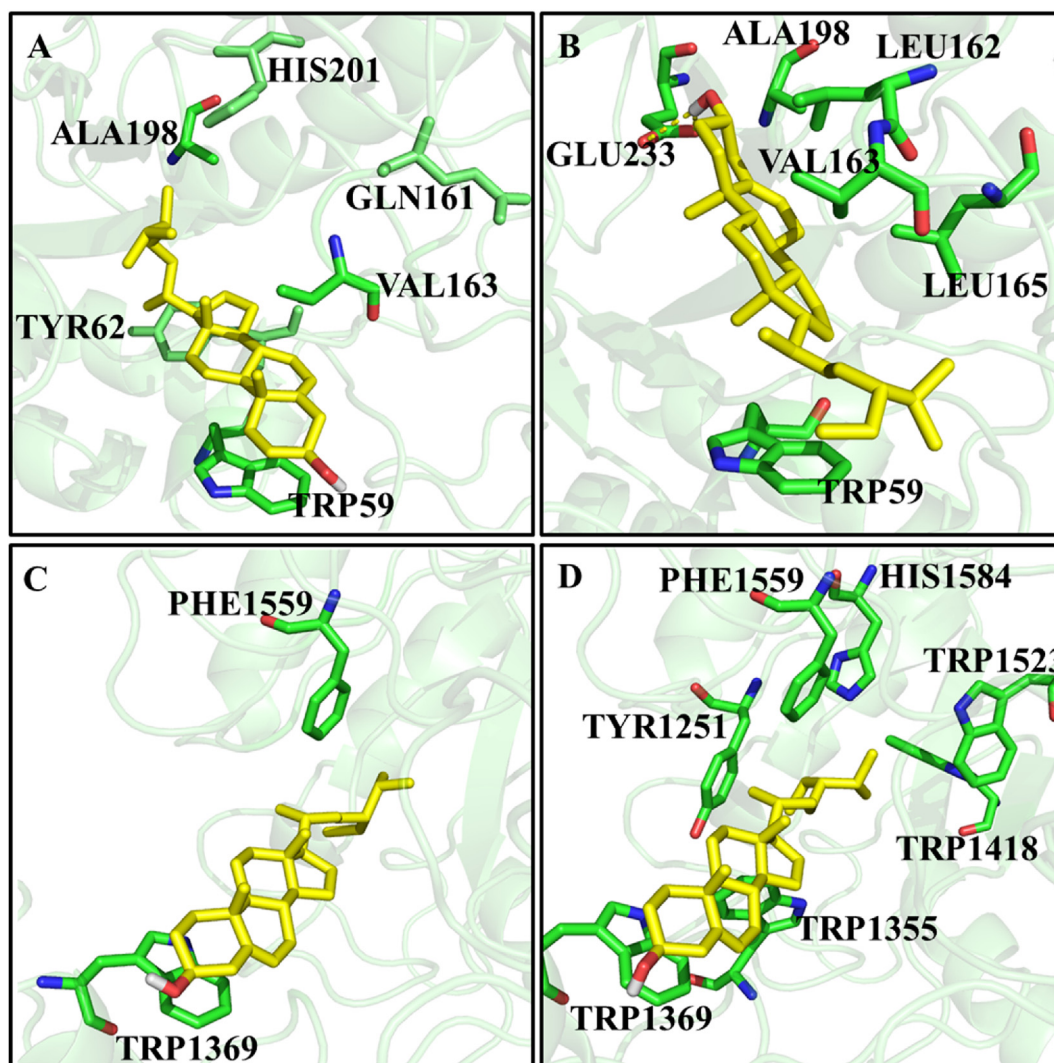
Figure 5. Molecular docking simulation results of chemical constituents of *Irvingia gabonensis* leaves extracts with protein targets. Superposition of α-amylase with the docked pose of Campesterol (A) and Stigmasterol (B); α-glucosidase with γ-Sitosterol (C) and Stigmasterol (D). Ligand structures are presented as yellow sticks while interacting amino acids of target proteins are shown as green sticks.

binding affinity to both enzymes (Table 3). The analysis of the interaction pattern of the compounds with the enzymes shows the interaction was majorly driven by hydrophobic factors.

Campsterol interacted with the amino acids at the binding site of α-amylase. The binding was stabilized by π-akyl interactions with TRP59, HIS201, π-δ interaction with TYR62, and alkyl interactions with LEU162, VAL163, and ALA198 (Figure 5a). Stigmasterol bound to α-amylase and formed π-δ and π-alkyl interactions with TRP59, the ligand also formed alkyl interactions with LEU162, VAL163, LEU165, and ALA198. A single H-bond was formed between stigmasterol and GLU233 with a bond length of 2.13Å (Figure 5b).

α-Glucosidase and γ-sitosterol formed a complex majorly via π-alkyl interactions with TYR1251, TRP1355, TRP1369, TRP1418, TRP1523, PHE1559, and HIS1584. One π-δ bond was found between γ-sitosterol and TYR1251. Stigmasterol on the other hand interacted with two amino acids of α-glucosidase namely: TRP1369 (π-alkyl and π-δ interactions) and PHE1559 (π-alkyl interaction).

Phenolic compounds and phytosterols found in plants are known to possess pharmacological effects. Phenolic compounds have proven antidiabetic effect through mechanisms that involve glycemic control (Kim et al., 2016; Lin et al., 2016). Similarly, phytosterols have been shown to possess antidiabetic and lipid lowering effects (Cedó et al., 2019; Vezza et al., 2020).

4. Conclusion

In summary, the present work evaluated the chemical composition of solvent extracts of *Irvingia gabonensis* leaves, determined the antioxidant and α-amylase and α-glucosidase inhibitory activity of the extracts. The results revealed that the aqueous and ethanol extracts had high phenolic content, antioxidant and α-amylase, and α-glucosidase inhibitory activity. It is concluded that the inhibitory effects of the plant extracts on enzymes linked to diabetes namely, α-amylase and α-glucosidase could be due to its phenolic content as well as other bioactive compounds identified by GC-MS analysis. This study provides evidence that inhibition of α-amylase and α-glucosidase is a mechanism by which *Irvingia gabonensis* exerts its antidiabetic effects.

Declarations

Author contribution statement

Francis O. Atanu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Arinzechukwu Ikeojukwu, Peter A. Owolabi: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Oghenetega J. Avwioroko: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data is available from authors upon request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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