



Soursop (*Annona muricata*) Nutritional Composition, Bioactivities and its Potential Applications: A Review

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Abstract

This article represented a review on soursop (*Annona muricata*), an edible fruit of the *Annona* in the custard apple tree family with emphasis on its skin (exocarp), pulp and seed. Likewise, extraction methods used to obtain active compounds from the skin (exocarp), pulp and seed as well as investigations on the bioactivities such as antioxidant, antidiabetic with some in vivo and in vitro studies were also enumerated. Current use in different food products as antioxidants, and as technofunctional ingredients was also elucidated. Since it is known that the development of alternative nutritive ingredients from under-utilized or less commercialized fruits is emerging. This necessitated the need to review the beneficial importance of soursop (skin, pulp and seed). The promising prospect of soursop is that juice obtained from its pulp pressing can be used in candies, flavouring, fruit bars, smoothies etc. Bioactive compound such as annonacin that is present in the seed may be used in cancer treatment.

Keywords Annonacin · Antioxidant · Extraction · Juice · Pulp · Seed · Utilization

Introduction

Fruits are very important from ancient time due to their beneficial status to promote health [1, 2]. They are vital in dietary guidance because they contain minerals particularly electrolytes, vitamins such as vitamin C, and phytochemicals which act basically as antioxidants, prompting fruits to gain global dominance [1, 3]. From scientific investigations, bioactivities and nutraceutical importance of fruits and

vegetables have been linked to reduction in death rate due to heart-related, cancer and other deteriorating illness among the human populace [4, 5]. These findings were attributed to bioactive compounds, dietary fiber and antioxidants components embedded in fruits and vegetables [6, 7].

Soursop (*Annona muricata*) is an edible fruit, of the *Annona* in the custard apple tree family that is made up of the skin, pulp and the seed (Fig. 1). They offer tremendous bioactivity attributes that could promote health [8–10]. The fruit was believed to have originated from West Indies and Central America within the lowlands region [11, 12]. It is also grown in the Caribbean, equatorial belts of the Americas such as in Cuba, Dominican Republic, Bahamas, Costa Rica, Bermuda, Grenada, Southern Mexico, Colombia, Ecuador and Brazil [12]. In southeast Asia, soursop is cultivated in Malaysia, Vietnam, Indonesia and Philippines as well as in Africa specifically in Nigeria [12, 13]. In Philippines, annual production was estimated to be around 8500 tonnes [14] while annual production of soursop in Mexico was approximately 35,000 metric tonnes in 1997 [12]. Hawaii produced around 16,000 lb per acre (roughly equal kg/ha). Puerto Rico estimated production was reported to be around 5000–8000 lb per acre [12, 15, 16]. Futuristically, the sporadic increase in human population across the globe may necessitate more fruits consumption thereby increasing

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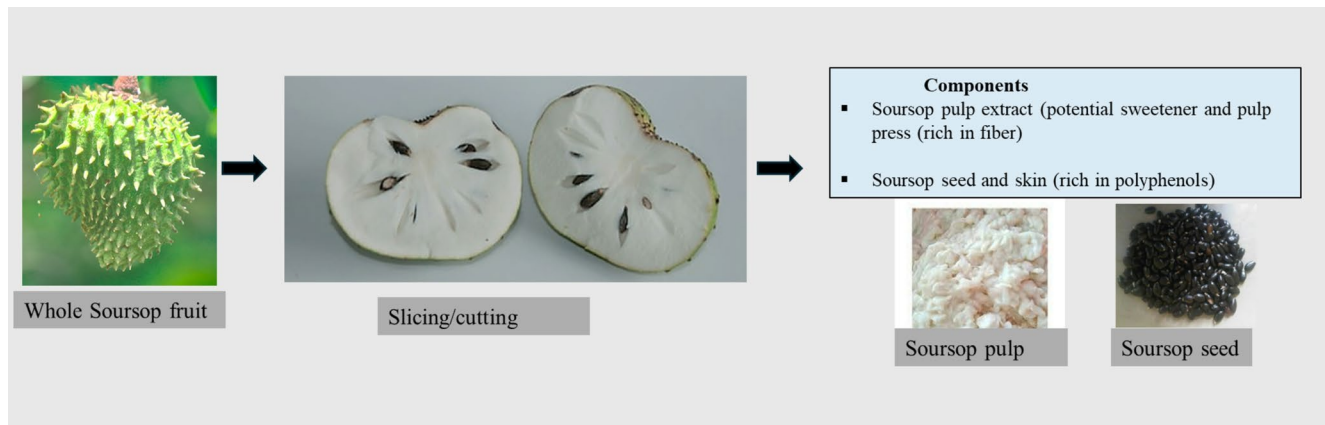


Fig. 1 Whole soursop fruit its pulp and seed

the demand for fruits including soursop. Hence it is anticipated that countries associated with soursop production could maximize its cultivation and distribution to boost their nation's revenues.

Soursop has a white pulp that consist of a distinctive sweet taste and aroma making it appealing to consume [17]. These sensory attributes offer additional advantage when considering market acceptability of the soursop pulp product or as co-ingredient in food industries [18, 19]. The pulp press remaining (by-product) consists of fiber and may serve as a potential additive in animal feed. Nevertheless, public and market awareness of the beneficial nutritive composition of soursop appears to be undermined. It is generally known that consumers only focus on the juice in the fruit for consumption and satisfaction while the skin and seeds are often discarded which contribute to waste. Elsewhere, Santos et al. [20], reported that huge wastes or leftovers are generated in the industries during juice extraction from soursop and they consisted of the peels, seeds, pulp press etc. It is important to investigate the nutritional composition, biological functions and potential applications of these wastes. Valorisation of the waste or fractions remaining into useful ingredients or compounds can further boost income and production. While strategies can be developed to reduce the generation of these wastes at postharvest levels and particularly in the industries.

Furthermore, it is known that food and pharmaceutical industries are seeking for nutritive ingredients from natural and cheap sources to meet the teeming consumer demand for healthy based food products. Therefore, opportunities exist for valorisation of soursop fruits, extracts, and seeds for it to be incorporated as an ingredient into developed nutritive products or supplements. In terms of scientific contribution, a review of the nutritional characteristics, different extractions methods employed to obtain extracts and biological functions of soursop fruits, extracts and seeds and general application of soursop (fruit, extracts and seeds) as

reported in different literature could give wholistic information which can serve as a guide to unlock the full potentials of soursop fruit.

Bioactive Compounds and Constituents of Soursop Pulp, Fruit and Seed

Natural bioactive compounds consists of phytochemicals and they help to improve human health [21, 22]. It has been reported that 40% of the drugs that was developed for medicinal use are derived from natural bioactive compounds [23]. These compounds are grouped into primary (carbohydrate, vitamins, ash, minerals protein, and fats) and secondary (polyphenols, flavonoids, alkaloids etc.) metabolites in plants [24]. Bioactive compounds are known to contribute to the different biological functions derived from soursop. The challenge associated with bioactive compounds is that they need judicious selection of unique or combination of several extraction techniques alongside sophisticated purification procedures to obtain purified extract with efficient biological activities. Some of the prominent bioactive compounds are presented in Table 1.

The crude carbohydrate content in soursop pulp and seed was reported to be 32.87 and 13.90%, respectively [25]. Soursop (particularly the pulp) consist of polysaccharides which are heavy molecular weights carbohydrates joined by glycosidic bonds which contribute to biological activities [26]. These polysaccharides contributes to the structural changes in the cell wall structure of soursop fruit during ripening and result to loss of firmness [27]. The presence of cell wall degrading enzymes such as pectin methyl esterase, cellulase and polygalacturonase have been attributed to the softening of the pulp during ripening [27]. Nevertheless, polysaccharides are known to be costly owing to the purification process during their production for commercial use.

Table 1 Some bioactive compounds reported in pulp, seed and skin of soursop as reported in literatures

Bioactive compounds	Pulp	Seed	Skin (peel)	References
β -amyrin		+		[48]
p-Anisic acid		+		[48]
4-Aminobenzoic acid		+		[48]
Apeginin		+		[48]
Benzoic acid			+	[49]
3,4 Dihydroxybenzoic acid		+		[48]
Caffeic acid		+		[48, 49]
Dicaffeoylquinic acid	+			[50]
Catechin		+		[48]
Carnosol		+		[48]
Chlorogenic acid	+	+	+	[48, 49]
Chrysin		+		[48]
Cinnamic acid	+	+	+	[48–51]
Coumaric acid			+	[49, 50]
Cyanidin			+	[51]
Ellagic acid		+		[48]
Ferulic acid		+		[48]
Gallic acid	+	+	+	[48, 49]
Kaempferol		+		[52]
Protocatechuic acid	+	+	+	[49]
Quercetin		+	+	[49, 51, 53]
Resorcinol			+	[51]
Salicylic acid		+		[48]
Sinapic acid		+		[48]
Syringic acid	+	+	+	[48, 49]
Vanillic acid		+	+	[48]
Vanillin		+	+	[48, 51]

The sign (+) indicated the presence of the listed bioactive compounds in the pulp, seed and skin/peel

Dietary fiber are polysaccharides such as resistant starches, inulin, hemicellulose, pectin, cellulose and gums [26]. It is well reported that the dietary fiber impact the digestion and absorption in the gastrointestinal tract owing to their structural complexity [26]. Furthermore, the consumption of dietary fiber have been linked to the reduction of chronic disease particularly those related to the gastrointestinal tract [26]. They also assist in gut performance and functioning [28]. Low cholesterol and blood sugar levels are associated with the presence of dietary fiber in human health [29]. The fiber content of 0.78–0.95% dw [11] and $44.46 \pm 1.13\%$ dw [26] was reported in soursop pulp and peel, respectively.

Saponins are glycosylated secondary metabolites that is mostly found in soursop seeds and they contribute to the astringent and bitter taste of soursop seed. Onyechi et al. [30] reported the saponin content of soursop seed to be 8.41 mg/100 g. Elsewhere, saponin content in aqueous extract of soursop seed was reported to be 1.2 ± 0.1 mg [31]. Saponins are known to be beneficial because they contribute to the anti-bacterial, anti-inflammatory, neuroprotective and antioxidants activities [32].

Polyphenols are the outcomes of biologically active plant that undergoes secondary metabolism [33]. Polyphenols consist of hydroxyl groups with one or more aromatic rings in its structure [34]. These polyphenols contribute to the taste and may also affect the functionality of soursop fruit. The total phenolic content in soursop pulp and seed extracts ranged between 19.84 and 50.15 mg catechin equivalents/g and 5.06–202.17 mg-catechin equivalents/g [35]. Flavonoids contents in the pulp was reported to be 224.7 ± 3.48 mg quercetin/g dw [36]. Elsewhere, the total phenolic and flavonoids content in the fresh pulp were 160.28 mg of GAE/100 g and 87.17 mg of quercetin/100 g, respectively [37]. Different protocols explored during these studies as well as variation in starting samples may account for differences in the polyphenol composition.

Soursop pulp consist of high amounts of water (76–83%), trace amounts of lipids (0.67–0.85%), proteins (0.26–1.03%) [11, 38–40]. The pulp also contain trace amount of minerals such as calcium (10.3), phosphorus (27.7), iron (0.64) and magnesium (0.04) in mg/100g [11]. It also consists of some vitamins such as A, B₁, B₂, B₃, C and E in 14.45, 0.11, 0.05, 1.28, 29.6 and 29 in mg/100 g as well as amino acids such as tryptophan (11), methionine (7) and

lysine (60) in mg/100g [11]. Esters of aliphatic acids e.g. methyl 2-butenate, ethyl 2-hexenoate, methyl 2-hexenoate and methyl 2-octenoate were identified as essential oil compounds in soursop pulp using gas chromatographic/mass spectrometric (GC/FID and GC/MS) [41]. Elsewhere, Bicas et al. [42] identified essential oil such as mono- and sesquiterpenes e.g., 1,8-cineole, (R)-terpineol, α -caryophyllene, linalool, linalyl propionate calarene in soursop pulp. Essential oils contains aromatic constituent, a mix of oily liquids and volatile compounds obtained by hydro, steam or dry distillation as well as by a mechanical press of a plant or its part that may require application of heat [43]. Nevertheless, more studies are recommended to develop an appropriate protocol for extraction of essential oil that is suitable for upscale for industrial use.

Soursop fruit consist of bioactive long chain fatty acid derivatives called *Annonaceous acetogenins* known as annonacin [44]. This compound forms a core part of the bioactivities attributes observed in soursop [11]. Likewise, flavonoid compounds such as Kaempferol and Quercetin have also been reported in soursop The structure of annonacin is illustrated in Fig. 2.

Soursop seed consist of 20–25% mass of the fruit and has been reported to contain oil of about 22.57% (dw) with yellow pale colour and protein (27.34%, (dw) trace amount of phytochemicals such as phytate, tannins, and cyanide that could be harnessed in human and animal nutrition [11, 45]. This oil possessed functional and nutritional properties that are related to edible oils from fruits such as cashew nut, groundnut and coconut [46, 47]. Summarily, the nutritive and chemical composition of soursop can be harnessed into nutritive ingredients by appropriate mix and selection of extraction method.

Extraction of Bioactive Compounds from Soursop

Extraction is governed by the extent of solubility of the various compounds together with other solutes embedded in a plant matrix [54, 55]. Therefore, a thorough homogenization of a plant tissue is crucial in order to enhance extraction rate [56]. Therefore, factors such as plant component matrixes, extraction solvent used, temperature and pressure parameters, extraction techniques may improve the

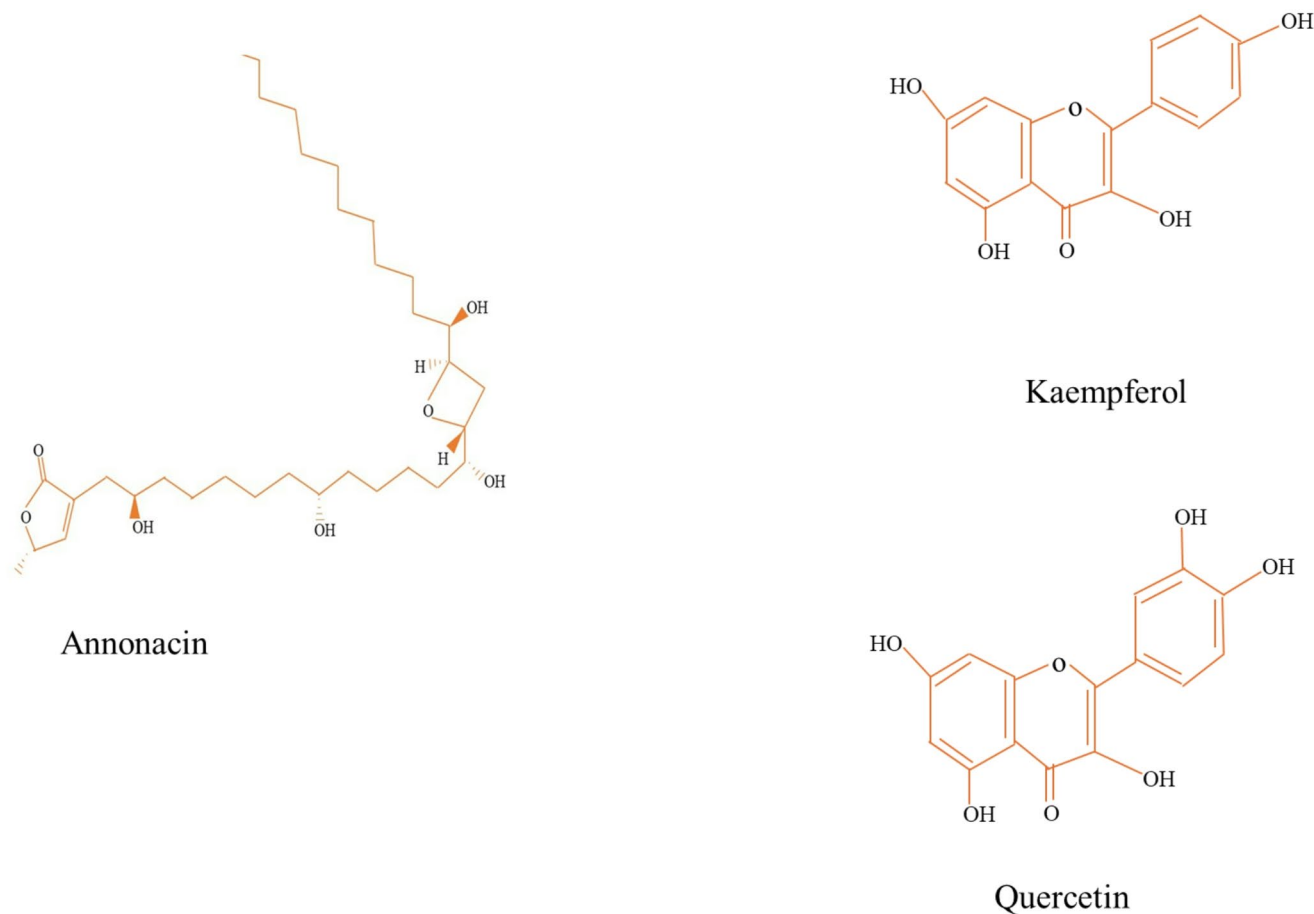


Fig. 2 Structure of Annonacin, Kaempferol and Quercetin

extraction efficiency [57]. A schematic description on the principle of extraction is illustrated in Fig. 3.

Judicious extraction of bioactive compounds especially heat sensitive compound from soursop could enhance their functional applications [37]. Limited information exist that aimed to describe the different extraction techniques used to obtain bioactive compounds or extracts from soursop. Therefore, this section highlighted some of the extraction methods adopted for extraction of bioactive compounds from soursop.

Aqueous and Solvent Extraction

Aqueous and solvent extraction is a recognised inexpensive method of extracting valuable and bioactive component from plant material. In different instances, liquid reagent such as buffer, distilled water, solutions containing lysis or surfactant are used during aqueous and solvent extraction [58]. More importantly, food grade reagents are widely considered for extraction of valuable and bioactive compound from plant material for consumption. The extraction of valuable and bioactive compounds using distilled water is identified as one of the simplest green extraction method [59]. This method is governed by the ratio of water to plant material suspension, temperature, stirring and centrifugation condition and pH. The yield of the extracts is generally low. For instance, Villacís-Chiriboga et al. [26] obtained dietary fiber by suspending soursop peel in distilled water (1:20 w/v) at temp of 80 °C and pH 5.76. This was followed

by filtration of the aqueous supernatant and then precipitation using 95% ethanol. Similarly, Iyanda-Joel et al. [60] obtained extract from soursop skin following using ethanol solvent extraction. The limitation of using solvent is associated with the low yield of compound that is often obtained.

Ultrasound Assisted or Sonication Extraction

The use of ultrasound assisted or sonication assisted extraction has gained prominent interest when considering extraction of bioactive compounds from plant material. Ultrasound involved the use of sound wave whose frequency may range between 20 kHz and 100 MHz [55]. The use of ultrasound generates a cavitation in liquids as well as in liquids that contain solids. This facilitates the accessibility of solvents into the cell components of the plant material [61]. Ultrasonic probe with horn transducers and ultrasonic water bath are the two different laboratory-based ultrasound that is widely used. The unique advantage of using ultrasound assisted extraction over the traditional or conventional extraction is that this technique requires short processing time, no organic solvent is required, relatively high yield and it prevent extract degradation [62]. A typical schematic example of an ultrasonic system set up is shown in Fig. 4A. Aguilar-Hernández et al. [63] extracted acetogenins from soursop pulp suspended in chlorofoam (1:5, w/v) followed by UAE extraction using ultrasound system (400 W, 24 kHz frequency) at acoustic power density of 300 W/cm² with maximum amplitude of about 175 µm. Though high yield of

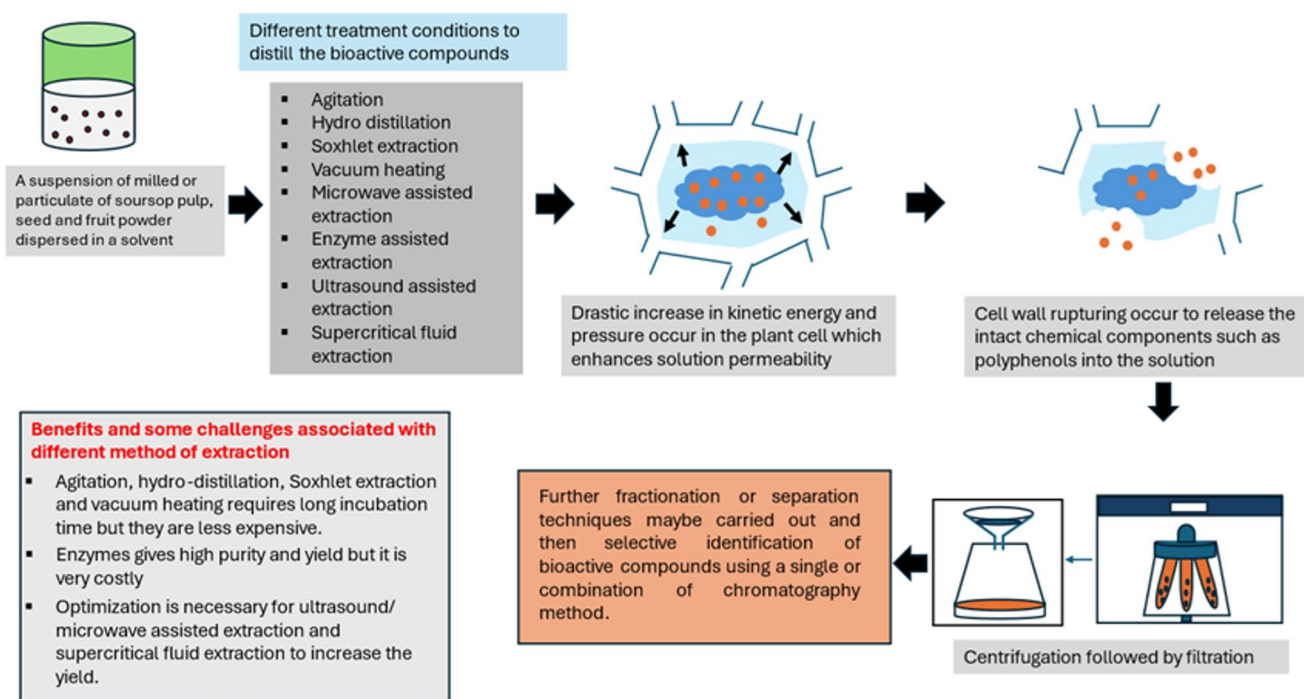


Fig. 3 A schematic description on the principle of extraction

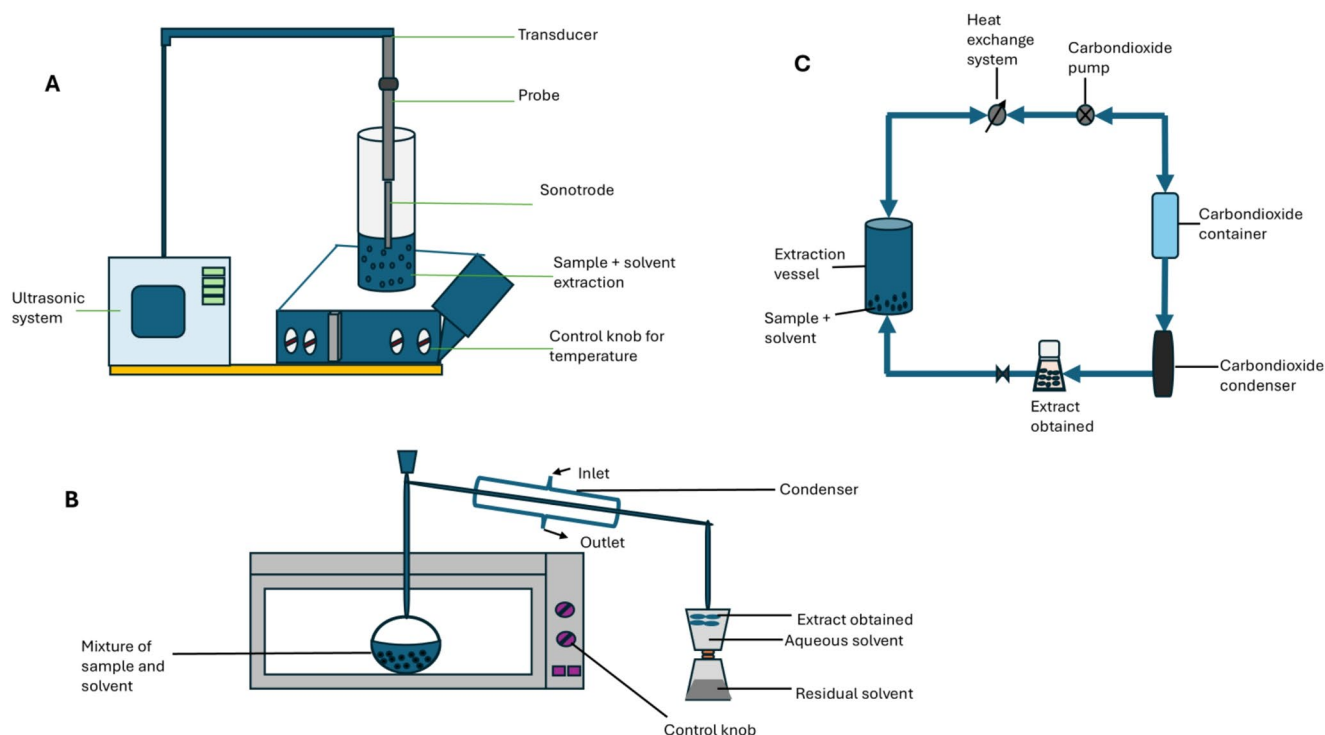


Fig. 4 A basic diagram of ultra-sound extraction (A), microwave (B) and supercritical fluid (C) set up

plant constituent can be obtained using ultrasound assisted extraction but this may require optimization of ultrasound parameters.

Microwave Assisted Extraction (MAE)

This method is associated with microwave heating of solid and liquid mixture. The heating is initiated by the microwave irradiation that is absorbed by molecules depending on their dielectric constant [59]. High dielectric constant polar molecules such as water (dielectric constant 78.5 at 25 °C) can absorb energy and emit the same which in turn heat up the system. Low dielectric constant solvent such as hexane (1.87 at 25 °C) are not sensitive to the microwaves [59]. The temperature is a vital specification for microwave assisted extraction of bioactive compounds. A typical schematic example of a microwave assisted extraction set-up is shown in Fig. 4B. Suzeta et al. [64] obtained extract from soursop peel using the microwave assisted extraction. Briefly, milled soursop peel powder was suspended at 1:10 (w/v) in different concentration of ethanol (50, 70 and 96%) followed by MAE method using a power of 420 W at duration between 3 and 7 min. Microwave assisted extraction is energy intensive and may require optimization to obtain optimum yield of plant extract.

Pressured Liquid and High Hydrostatic Pressure (HPP) Extraction

Pressured liquid extraction is a process whereby the extraction solvent is heated up above its boiling point using pressure. This procedure is governed by the concept that higher temperature greater than those used during conventional extraction leads to higher solubilization of the desired bioactive compounds from the plant cell in a solute-matrix interaction [59].

On the otherhand, HPP extraction induce the biological tissues of plant materials owing to liquid pressurization which can be as high as 1000 bars [65]. The choice of solvent/liquid, duration, operating temperature and pressure are vital to obtain bioactive compounds using this procedure [65]. This method is also suitable for extraction of thermally sensitive bioactive compounds. Although, no studies appear to have reported the use of pressurized liquid or HPP extraction to obtain bioactive compounds from soursop fruits, peels and seeds.

Supercritical Fluid Extraction

Supercritical fluid extraction depends on the liquid and gas properties, high density and solvent diffusivity to increase mass transport of bioactive compounds [66]. A typical schematic example of a supercritical fluid extraction set-up is shown in Fig. 4C. Mesquita et al. [48] employed this

concept for recovery of extracts from soursop seeds using a supercritical CO₂ at 20 MPa, temperature of 50°C and a solvent flow rate of 0.7 kg/h. The information presented herein indicated the possibility to extract bioactive compounds from soursop fruit, peel and seeds. It is capital intensive and requires energy for optimum functioning.

Enzyme Assisted Extraction

Enzymes are biological catalyst and they can be derived from diverse sources. e.g. animal organs, bacteria, fruits and plants extracts [67, 68]. Enzymes assist to disintegrate the rigid plant cell wall which enhance the permeability and diffusion of solvents into the cell wall components [69]. This step improved the extraction yield of bioactive materials obtained from the plant material. The selection of appropriate incubation time and temperature, enzyme concentration as well as optimal pH is crucial to enhance the enzyme activity. Chang et al. [70] obtained a puree from soursop pulp using enzyme treatment such as Fungamyl® 800 L, Celluclast® 1.5 L, Pectinex® Ultra SP-L at a concentration of 1.5% (v/w). Overall, extraction of desired bioactive components from soursop following the appropriate selection method could enhance their biological function in cells, food systems or as bioactive ingredients in food products. It is well documented that enzymes are very costly and if considered for extraction may impact the overall cost of the extraction process.

Bioactivities of Soursop

Extracts from soursop (skin, peel and seeds) have been tested for a wide range of bioactivities such as antioxidant, antidiabetic, anticancer etc. The result of some of the findings in the literature are summarized in this section.

Antioxidant Activities

Antioxidants are known in the human body cells, food system and tissues to limit oxidative destruction from free radicals [71, 72]. Reactive oxygen species (ROS) and free radicals are products of cellular respiration in human body and also in aerobic organisms [73]. Due to their instability free radicals react swiftly with other molecules in humans which result in cell or tissue damage to the body. Also, they can trigger some known diseases such as heart disease, cancer, Alzheimer's and Parkinson's disease [74]. In a food system, reactive oxygen species and free radicals are known to promote lipid oxidation in food products while processing and storage which produced toxic reaction products as well as unwanted off flavour [75]. Hence, synthetic antioxidants

like propyl gallate (PG), butylated hydroxyl anisole (BHA), butylated hydroxyl toluene (BHT) and tertiary butyl hydroquinone (TBHQ) are used. However, synthetic antioxidants are reported to be carcinogenic [76]. This shifted attention to natural antioxidants from food.

Some of the investigations on antioxidant activities of soursop skin, pulp and seeds are presented herein. For instance, Lee et al. [77] reported the antioxidant activities of extracts from peels of soursop following tested bioassays such as DPPH radical scavenging assay, ABTS radical inhibition activity, β -Carotene linoleate bleaching assay and Ferric-reducing antioxidant power (FRAP). The EC₅₀ values of the extract was observed to be 1179.96 and 145.12 μ g/ml, from DPPH and ABTS assays, respectively. The study also showed that β -Carotene linoleate bleaching assay (80.08%) and FRAP value (58.9 μ g TE/ml extract). It was concluded that peel from soursop could serve as cheap source of natural antioxidants for use in the food industries. This was corroborated by Iyanda-Joel et al. [60] investigation whereby ethanolic extract from skin of *soursop* exhibited some antioxidant properties at the tested concentration.

Extract from different parts of soursop including the pulp was subjected to DPPH radical scavenging assay, Ferric-reducing antioxidant power (FRAP) assay and Hydroxyl radical scavenging ability. The tested extracts indicated varying capacities of antioxidant activities in various assays [78]. This correlated with the report from Adefegha et al. [72] that soursop fruit (seed, pulp and pericarp) have antioxidant activities. Studies from Martínez-Mendoza et al. [79] on fermented soursop pulps and further confirmed their antioxidant activities.

Antidiabetic and Anticancer Properties

Natural plant extracts with antidiabetic properties was reported to be preferred than using medication for management of diabetes because they can increase insulin generation and lower intestinal glucose intake [80]. It was also reported that the current medications used for the management of diabetics are effective but they possess some negative side effects such as disruption of genetic and metabolic pathway [80]. Meanwhile, soursop fruit extracts demonstrated inhibitory effect on α -amylase and α -glucosidase activities by altering blood glucose level and their inhibition which significantly reduce the postprandial increase of blood glucose [72, 81].

Increase risk of exposure from chemotherapy and radiotherapy treatment for cancer have prompted continuous search for bio-materials from natural sources that have anticancer properties [7]. Meanwhile, soursop fruit have been investigated for its growth inhibition against cancer cells using lung carcinoma cell lines, solid breast cancer, colon

and prostate adenocarcinoma cell lines have been reported [82, 83]. Another study further established the efficacy of pulp and peel extract from soursop to function as an anticancer agent when tested on liver cancer Hep2 cell line to confirm their activities against cancerous proliferation [84].

Briefly, the highlights presented above are pointer to the potential biological functioning of soursop. Nevertheless, more investigations is suggested when considering appropriate safety consumption of bioactive compounds from soursop and their applications as bioactive agent in nutraceutical products.

Traditional Medicinal and Therapeutic Application

The evolution soursop fruit application have been in existence from ancient times [85], whereby soursop fruits with seeds were prepared alone or in addition with other herbal component to make decoctions, juices, infusions for traditional use to manage human ailments and diseases. Countries such as Bolivia, Brazil, Malaysia, Nigeria, Thailand, Uganda and in many other countries across the globe were known to engaged in ortho-medical practices using different plants and fruits sources including soursop [86]. However, the mechanism, mode of action and bioactive compounds responsible for these therapeutic activities could not be validated in ancient times due to limited scientific exploitation. Modern scientific investigations and findings have identified the presence of bioactive compounds and their therapeutic mechanisms in soursop that explained their therapeutic function in traditional medicine. Some of the reported orthodox applications are briefly presented in this section and highlighted in Table 2.

Soursop fruit was prepared as juice for management and treatment of different diseases such as kidney disorder and hypertension in Bolivia [87], diarrhea, lactagogue, astringent and dysentery in Brazil [11], for inflammation and

febrifuge treatment in Colombia [88], stomach pain and hypertension in Malaysia [89], dysentery and diabetes in Mexico [90], decoctions and juices are made from unripe fruit, seed as well as leave for treatment of prostate cancer, diabetes neuralgia, rheumatism, gastric disorders and arthritic pain in Nigeria [91–93], fruit to make obesity, gastritis, dyspepsia, diabetes, inflammation in Peru [11], decoctions are made from seed with leaf, bark and root for treatment of catarrh, insomnia and febrifuge in Benin [94]. Overall, appropriate scientific innovations may need to be investigated for extraction of bioactive compounds from soursop for their development in polyherbal tea or function food aimed for therapeutic use.

Some Applications of Soursop in *in Vivo* and *in Vitro* Experiments

Some investigations on *in vivo* and *in vitro* experiments have been carried out to investigate the pharmacological activities of soursop. Analgesic and anti-inflammatory activity of lyophilized soursop fruit extract was confirmed in a study by Ishola et al. [95]. Alkaloids compounds such as annonaine, nomuciferine and asimilobine extracted from soursop fruit was reported to inhibit 5-HTergic 5-HT_{1A} receptor (anti-depressive activity) in rats [96, 97]. Elsewhere, *Annonaceous acetogenins* from soursop fruit indicated inhibition activities against prostate PC-3 cancer cells [98]. Similarly, bioactive compound cis-mono-tetrahydrofuran rings acetogenins from soursop seed indicated crown gall tumor inhibition, breast MCF-7 and lung A549 cancer cells [14] while acetogenins inhibited toxicity against human hepatoma cells [99]. Soursop seed oil orally administered to mice exhibited antihyperglycemic effect [100]. Liaw et al. [82] reported the efficacy of acetogenins compounds such as cisannomontacin and muricin against two human hepatoma cell lines, Hep G2 and 2,2,15 in cytotoxicity assay indicating its efficiency for treatment of liver cancer.

Table 2 Some soursop constituents used for orthodox medicinal and therapeutic applications

Soursop constituent/preparation	Country associated with usage	Orthodox medicinal and therapeutic applications	References
Soursop fruit/juice	Bolivia	Kidney disorders, hypertension	Hajdu and Hohmann [87]
Soursop fruit/juice	Brazil	Diarrhea, lactagogue, astringent and dysenter	Badrie and Schauss [11]
Soursop fruit/juice	Colombia	Inflammation and febrifuge	Betancur-Galvis et al. [88]
Soursop fruit/juice	Malaysia	Stomach pain and hypertension	Samuel et al. [89]
Soursop fruit/juice	Mexico	Dysentery and diabetes	Alonso-Castro et al. [90]
Soursop unripe fruit with seed and leaf/decoction and juice	Nigeria	Prostate cancer, diabetes neuralgia, rheumatism, gastric disorders and arthritic pain	[91–93]
Soursop fruit/pulp and juices	Peru	Obesity, gastritis, dyspepsia, diabetes, inflammation	Badrie and Schauss [11]
Soursop seed with leaf, bark and root/decoction	Benin	Catarrh, insomnia and febrifuge	Kossouh et al. [94]

Table 3 Applications of soursop pulp, seeds, oils and other constituents in food products

Material source	Products	Result	References
Soursop pulp	Soursop yoghurt and soursop frozen dessert	Improvement in dietary fiber, vitamin C and total polyphenol	Virgen-Ceceña et al. [102]
Soursop, milk and honey	Dietary soursop milkshake	Ascorbic acid, antioxidant activity and acceptable sensory characteristics	Olagunju and Sandewa [103]
Yogurt blackberry and soursop	developed formulated beverage	Antioxidant properties	Zambrano et al. [104]
soursop juice and soursop nectar /pulp	Yoghurt/probiotic yoghurt	Improved physicochemical properties and antioxidant activities/acceptable sensory attribute	Dias and Jayasooriya [106, 108]
soursop with moringa leaf powder	ice cream	antioxidant, low glycemic index and sensory attributes	Ademosun [107]
Pineapple, orange and soursop	pure and mixed fruit juices	Nutritive and sensory attribute	Ani et al. [119]
Soursop pulp	Beer (beverage)	Nutritive and sensory quality	Santos et al. [109]
soursop	Vinegar (beverage)	Sensory acceptability of soursop vinegar was less sour and sweeter than commercial vinegar	Ho et al. [112]
Soursop pulp	Inulin-enriched soursop whey beverage	Maintains the physicochemical and color	Silva et al. [113]
Soursop seed oil	cream	Exhibited favourable physicochemical properties and was incorporated into creams as emollient and antioxidant excipient	De Lima Souza et al. [114]
Soursop	puree	Sensory attribute maintained	Martínez-Moreno et al. [115]
Soursop pulp	Juice	Good sensory attribute	Yusof and Ibrahim [116]
Soursop residue (leftover of peels, seeds and squeezed pulp) flour with wheat flour	Bread	Good sensory attribute	Saavedra et al. [117]
Soursop juice	Fermented beverage	Good sensory attribute	Tan et al. [118]

These findings indicated the potential of soursop extracts from flesh, pulp and seed to function as nutraceuticals agents in the pharmaceutical industries. A comprehensive clinical/human trial is deemed necessary to validate their potencies in the physiological conditions of humans.

Applications of Soursop in some Developed Foods Products

Soursop is attracted to consumers due to the pleasant and distinct flavour of the fruit and its white pulp [101]. The pulp has been marketed in Brazil, North America and Europe with its application ranging from manufacturing of food products such as ice-cream, puree, jams, shakes, jellies, yoghurt, syrups and juice blends [101].

Some of the applications of soursop fruit are highlighted in Table 3. For instance, Virgen-Ceceña et al. [102] investigated the nutritional and sensory attribute of yoghurt and frozen dessert formulated with soursop pulp. The result indicated an improvement dietary fiber (0.92 and 2.17%), vitamin C (11.25 and 9.84 mg/100 g) and total polyphenol (243.02 and 490.98 mg/100 g). A drink from blends of soursop, milk and honey (dietary soursop milkshake) was developed and was subjected to proximate, physicochemical, antioxidant, sensory and microbial properties [103]. The

formulated milk shake contained ascorbic acid 28.67–44.00 (mg/100 mL), high antioxidant activity. Also, addition of milk improved their drink also produced a high flavonoid content and antioxidant properties (DPPH scavenging activity) with acceptable sensory characteristics. Similarly, a developed formulated beverage made from yogurt blackberry and soursop exhibited antioxidant properties [104]. Akomolafe and Ajayi [105] reported that peel and pulp of ripe soursop fruit exhibited antioxidant activities. Thus, they could serve as natural antioxidant for functional food and pharmaceutical applications. Soursop juice and nectar were incorporated into yoghurt formulations with comparison to that without soursop which serve as control [106]. These formulations were tested for physicochemical and antioxidant properties. Soursop juice yoghurt had nearly two times high protein (7.67%) content when compared to control (4.34%). Soursop nectar developed yoghurt indicated the highest sensory acceptance. Highest DPPH radical scavenging percentage was observed in soursop juice yogurt (13.87% – 85.53%) followed by soursop nectar yogurt (4.13% – 71.96%) than the control (0.44% – 17.92%). The developed yoghurts exhibited desirable sensory attributes with improved physicochemical and antioxidant activities. Investigations on soursop ice cream with moringa leaf powder possessed good antioxidant, low glycemic index and sensory attributes [107]. Similarly, probiotic yoghurt using

soursop, sweet sop and custard apple with acceptable sensory attribute have been developed [108].

Natural fruits blend from pineapple, orange and soursop was processed and subjected to nutritional and sensory assessment. The blend of 30% Pineapple, 30% Orange and 40% Soursop had crude protein 1.1%, fat 0.5%, dietary fibre 0.46% and calorie 0.9% with carbohydrate 18.68%. It also possessed good sensory properties such as aroma taste, sweetness, flavour and overall acceptability. Soursop pulp was incorporated into craft beers (beverage) and from the study ash 0.2 g/100 g, lipids 0.02 g/100 g, proteins 0.14 g/100 g and, among minerals, calcium and sodium were predominant in the beverage. The beverage also was reported to showed acceptable sensory quality [109].

Vinegar is referred to as a healthy beverage due to its ability to lowers blood sugar in the presence of probiotics [110]. Production of vinegar from fruit uses the sugar naturally present in the fruit, which gives a vinegar good organoleptic properties [111]. A study on the fermentation of soursop juice using alternative starter cultures (yeast and mushroom) to produce soursop wine (alcoholic fermentation). It was concluded that alcoholic beverage can be produce from soursop fruit [112].

Inulin-enriched soursop whey beverage, a prebiotic carbohydrate was produced and analyzed using supercritical fluid carbondioxide which did not alter physicochemical and color changes in the prebiotic whey beverage processed [113]. A study on the possibility of extracting oils from soursop seed industrial waste have been conducted [114]. In the study, the soursop seed was subjected to different mechanical and chemical means of extraction. The oils obtained exhibited favourable physicochemical properties and was incorporated into creams as emollient and antioxidant excipient. The findings suggest that the oils can be used as emollient and antioxidant to replace the synthetic ingredients incorporated (butylhydroxytoluene, liquid petrolatum and decyl oleate), originated formulations with adequate physical and chemical stability. Soursop puree was processed through the combined effect of vacuum, heat and ultrasound (vacuum-thermosonation). The study reported that the processing conditions did not alter the sensory attribute of the soursop puree. It was recommended that the puree could be used in fruit based-beverages (juice and nectar) as well as in milk and its derivatives [115]. Soursop juice was extracted from the pulp with the aid of pectinase enzyme. The use of the enzyme increased the yield by 41% with a good sensory attribute [116]. Partial incorporation of soursop residue (leftover of peels, seeds and squeezed pulp) flour with wheat flour was used to develop bread with good sensory acceptability [117]. Tan et al. [118] developed a fermented beverage (Kombucha) using a combination of soursop juice, sugar and black tea. It is known that food

structure, physicochemical properties as well as processing of soursop skin (exocarp), pulp and seeds can greatly affect the bioaccessibility of inherent phytochemical and constituent nutrients. Hence, soursop skin (exocarp), pulp and seeds and associated developed food products should be assessed for bioaccessibility and biodigestibility prior to commercial production and consumption.

Considerations for Future Outlooks

Soursop skin (exocarp), pulp and seeds have unique compositions that are useful in a wide range of food applications, pharmaceuticals, cosmetics and in agriculture (animal feed) and even in non-food products (bioplastics or biodiesel). These diverse potential applications, if properly harnessed, can generate more income to the growth and development of regions that grow soursop fruit. GC-MS analysis of soursop pulp indicated the presence of essential oil such in a study by Gyesi et al. [120]. The essential oil identified were basically aliphatic compounds and phytosterols. In general, essential oils are known to contribute to biological functioning such as oxidative stability owing to the numerous diverse compounds that are present in these oil [121]. Huang et al. [122] reported the possibility of essential oil to function as antimicrobial and for seafood preservation. Therefore, it may be necessary to further investigate the possibility of soursops functioning as antimicrobial to expand their range of applications in food industries.

The synthesis of bio-flavour based on bioconversion of food waste using micro-organisms is gradually gaining prominence because it limit the use of expensive chemical components in media formulation and allows economical production of flavorant by fermentation [123]. The concept involves using enzymatic, microbiological and biotechnological methods to obtain the desired flavour compounds. Elsewhere, Kowalska et al. [124] reported the possibility of essential oil to serve as flavorant. Thus, opportunities exist for the use of essential oil from soursop for use as a flavorant.

The concept of zero waste by valorisation of waste may be a useful concept when considering the application of soursop seed press by products (cake). It is known that seed press byproducts are source of fibers, vitamins, minerals, phenolic compounds and may found useful applications in different products [125]. For instance, these byproducts may be used as additives in animal feeds and as flour or concentrate for use in confectionery industries. On the other hand, remnants from the soursop pulp press which can serve as a fiber source may also be considered for use as concentrates in roughages.

Extraction and identification of bioactive compounds from soursop provides convincing evidence to support their potential use in future drug discovery systems, especially in the key areas such as antioxidant, antidiabetic and anti-cancer functioning. It can also serve as a guide when considering unlocking their full therapeutic potential. It is an established fact that consumer demand for new health products is increasing which has challenged food industries to innovate and developed new food products based on scientific findings. This creates an opportunity for the consideration of soursop pulp and seed oil which can be fractionated to obtain different nutritive ingredients such as fiber, sugars and oil suggest for development or enhancement of new or existing products.

The issue surrounding sustainable production of fruits such as soursop may need to be revisited. This is very important particularly for industries who are interested in developing products on a large scale using bioactive material from soursop. Furthermore, different laboratory studies and protocols currently used for extraction of bioactive compounds from soursop may need to be tested on a large scale to ascertain the extraction efficiency when considering obtaining nutritive and bioactive compounds from soursop in large quantities. This will allow industries project feasibility cost and likely profitability when proposing large scale products development from soursop fruits and its byproducts.

Conclusion

This review inferred that soursop (specifically the skin, pulp and seed) possess enormous nutritive and phytochemical components. Careful selection of extraction procedures can be followed to obtain bioactive compounds in soursop. These bioactive compositions were responsible for their promising biological functions. Some of the studies reported on the applications of soursop in beverages and food products confirmed that they can be used as nutritive ingredients in the food industries. New and existing food, agro-allied and pharmaceutical industries should consider incorporating ingredients developed from soursop in the formulation of functional food/feed products.

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Declarations

Competing Interests The authors hereby declare herein that they have no competing interest.

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References

1. Igiehon, O.O., Adekoya, A.E., Idowu, A.T.: A review on the consumption of vended fruits: Microbial assessment, risk, and its control. *Food Qual. Safe.* **4**(2), 77–81 (2020)
2. Vayalil, P.K.: Date fruits (*Phoenix dactylifera* Linn): an emerging medicinal food. *Crit. Rev. Food Sci. Nutri.* **52**(3), 249–271 (2012)
3. Slavin, J.L., Lloyd, B.: Health benefits of fruits and vegetables. *Advan Nutri.* **3**(4), 506–516 (2012)
4. Dillard, C.J.: German, phytochemicals: Nutraceuticals and human health. *Journ Sci. Food Agric.* **80**(12), 1744–1756 (2000)
5. Ahmad, F., Zaidi, S.: Role of By-products of fruits and vegetables in functional foods. In: *Functional Food Products and Sustainable Health*, 199–218. Springer (2020)
6. Prior, R.L., Cao, G.: Antioxidant phytochemicals in fruits and vegetables: Diet and health implications. *HortScience.* **35**(4), 588–592 (2000)
7. Maqsood, S., Adiamo, O., Ahmad, M., Mudgil, P.: Bioactive compounds from date fruit and seed as potential nutraceutical and functional food ingredients. *Food Chem.* **308**, 125522 (2020)
8. Gavamukulya, Y., Wamunyokoli, F., El-Shemy, H.A.: *Annona muricata*: Is the natural therapy to most disease conditions including cancer growing in our backyard? A systematic review of its research history and future prospects. *Asian Pac. Journ Trop. Med.* **10**(9), 835–848 (2017)
9. Menezes, E.G.T., Oliveira, E.R., Carvalho, G.R., Guimaraes, I.C., Queiroz, F.: Assessment of Chemical, Nutritional and Bioactive Properties of *Annona Crassiflora* and *Annona Muricata* Wastes. *Food Sci Techn (AHEAD)* (2019)
10. George, V.C., Kumar, D.N., Suresh, P., Kumar, R.A.: Antioxidant, DNA protective efficacy and HPLC analysis of *Annona muricata* (soursop) extracts. *Journ Food Sci. Techn.* **52**(4), 2328–2335 (2015)
11. Badrie, N., Schauss, A.G.: Soursop (*Annona muricata* L.): Composition, nutritional value, medicinal uses, and toxicology, in bioactive foods in promoting health. Elsevier 621–643 (2010)
12. Sanusi, S.B., Bakar, M.F.A.: Soursop—*Annona Muricata*, in *Exotic Fruits*, pp. 391–395. Elsevier (2018)

13. Madurangi, G.W.S., Gunathilake, D.: Development of an antioxidant rich beverage using soursop fruit and ginger extract. *Ann. Food Sci. Technol.* **17**, 179–185 (2016)
14. Rieser, M.J., Gu, Z.-M., Fang, X.-P., Zeng, L., Wood, K.V., McLaughlin, J.L.: Five novel mono-tetrahydrofuran ring acetogenins from the seeds of *Annona muricata*. *Journ Nat. Prod.* **59**(2), 100–108 (1996)
15. Sawant, T.P., Dongre, R.S.: Bio-chemical compositional analysis of *Annona muricata*: A miracle fruit's review. *Internat Journ Univer Pharm. Bio Sci.* **2**(3), 82–104 (2014)
16. Love, K., Paull, R.E.: *Soursop*. (2011)
17. Pinto, A., Cordeiro, M., De Andrade, S., Ferreira, F., Filgueiras, H., Alves, R., Kinpara, D.: *Annona* Species. *Embrapa cerrados-livro Científico (ALICE)*. International Centre for Underutilised Crops, Southampton (2005)
18. Athira Babu, D., Saranya, S.: Standardisation and sensory quality analysis of nutritious product from an Indigenous fruit (*Annona muricata*). (2019)
19. Portela, J.B., Guimaraes, J.T., Lino, D.L., Brito Sass, C.A., Pagani, M.M., Pimentel, T.C., Freitas, M.Q., Cruz, A.G., Esmerino, E.A.: Statistical approaches to determine emotional drivers and improve the acceptability of prebiotic Whey soursop beverage processed by ultrasound. *Journ Sens. Stud.* e12733 (2021)
20. Santos, I.L., Rodrigues, A.M.D.C., Amante, E.R., Silva, L.H.M.D.: Soursop (*Annona muricata*) properties and perspectives for integral valorization. *Foods*. **12**(7), 1448 (2023)
21. Li, Z., Fan, Y., Xi, J.: Recent advances in high voltage electric discharge extraction of bioactive ingredients from plant materials. *Food Chem.* **277**, 246–260 (2019)
22. Riar, C.S., Panesar, P.S.: *Bioactive Compounds and Nutraceuticals: Classification, Potential Sources, and Application Status, in Bioactive Compounds and Nutraceuticals from Dairy, Marine, and Nonconventional Sources*, pp. 3–60. Apple Academic (2024)
23. Xiao, J., Chen, G., Li, N.: Ionic liquid solutions as a green tool for the extraction and isolation of natural products. *Molec.* **23**(7), 1765 (2018)
24. Xiang, B., Zhou, X., Qin, D., Li, C., Xi, J.: Infrared assisted extraction of bioactive compounds from plant materials: Current research and future prospect. *Food Chem.* **371**, 131192 (2022)
25. Osei, P.A., Kpodo, F.M., Tettey, C.O., Dzah, C.S., Agbenorhevi, J.K., Hunkpe, G., Nanga, S.: Proximate composition, phenolic, and antioxidant properties of soursop fruit parts. *CyTA-Journ Food.* **21**(1), 475–480 (2023)
26. Villacis-Chiriboga, J., Zaldumbide, E., Raes, K., Elst, K., Van Camp, J., Ruales, J.: Comparative assessment of physicochemical, structural and functional properties of dietary fiber extracted from Mango (*Mangifera indica* L.) and soursop (*Annona muricata*) peels. *Int. Journ Biolog Macromolec.* **238**, 124116 (2023)
27. Ren, Y., Sun, P., Wang, X., Zhu, Z.-Y.: Degradation of cell wall polysaccharides and change of related enzyme activities with fruit softening in *Annona squamosa* during storage. *Postharv Biol. Technol.* **166**, 111203 (2020)
28. Clauss, M., Gérard, P., Mosca, A., Leclerc, M.: Interplay between exercise and gut Microbiome in the context of human health and performance. *Front. Nutrit.* **8**, 637010 (2021)
29. Wang, S., Fang, Y., Xu, Y., Zhu, B., Piao, J., Zhu, L., Yao, L., Liu, K., Wang, S., Zhang, Q.: The effects of different extraction methods on physicochemical, functional and physiological properties of soluble and insoluble dietary fiber from *rubus Chingii* hu. fruits. *Journ Funct. Foods.* **93**, 105081 (2022)
30. Onyechi, U., Ibeanu, V., Eme, P., Ugwuanyi, C.: Nutrient and photochemical composition of *Annona muricata* seed flour (soursop). *Journ Dietit. Assoc. Nigeria.* **5**(4), 46–55 (2014)
31. Hernández-Guerrero, S.E., Balois-Morales, R., Bautista-Rosales, P.U., López-Guzmán, G.G., Berumen-Varela, G., Palomino-Hermosillo, Y.A., Jimenez-Zurita, J.O., Bello-Lara, J.E., León-Fernandez, A.E.: Identification of fungal pathogens of Mango and soursop fruits using morphological and molecular tools and their control using Papaya and soursop leaf and seed extracts. *Internat Journ Agron.* **2020**, 1–15 (2020)
32. Rawa, M.S.A., Hassan, Z., Murugaiyah, V., Nogawa, T., Wahab, H.A.: Anti-cholinesterase potential of diverse botanical families from malaysia: Evaluation of crude extracts and fractions from liquid-liquid extraction and acid-base fractionation. *Journ Ethnopharmac.* **245**, 112160 (2019)
33. Zagorskina, N.V., Zubova, M.Y., Nechaeva, T.L., Kazantseva, V.V., Goncharuk, E.A., Katanskaya, V.M., Baranova, E.N., Aksenova, M.A.: Polyphenols in plants: Structure, biosynthesis, abiotic stress regulation, and practical applications. *Internat Journ Molec Scie.* **24**(18), 13874 (2023)
34. Belščak-Cvitanović, A., Durgo, K., Hušek, A., Bačun-Družina, V., Komes, D.: Overview of Polyphenols and their Properties, in *Polyphenols: Properties, Recovery, and Applications*, pp. 3–44. Elsevier (2018)
35. Orak, H.H., Bahriseft, I.S., Sabudak, T.: Antioxidant activity of extracts of soursop (*Annona muricata* L.) leaves, fruit pulps, peels and seeds. *Pol. Journ Food Nutrit Sci.* **69**(4) (2019)
36. Ogunkunle, M., Akano, A., Kukoyi, T.: Quantification of total phenolics, flavonoids and antioxidant activities of three selected tropical fruits grown in Nigeria. *Agricultural Food Sci. Journ Ghana.* **13**, 1175–1185 (2020)
37. Neta, M.T.S., de Jesus, J.L.A., da Silva, H.C.S., Araujo, R.D.D., Sandes, S., Shanmugam, Narain, N.: Effect of spray drying on bioactive and volatile compounds in soursop (*Annona muricata*) fruit pulp. *Food Res. Intern.* **124**, 70–77 (2019)
38. Moreno-Hernández, C.L., Sáyo-Ayerdi, S.G., García-Galindo, H.S., Mata-Montes, M., De Oca, Montalvo-González, E.: Effect of the Application of 1-methylcyclopropene and Wax Emulsions on Proximate Analysis and some Antioxidants of Soursop (*Annona Muricata* L). *The Scient World Journ* (2014)
39. Vwioko, D.E., Osemwegie, O.O., Akawe, J.N.: The effect of Garlic and ginger phytonics on the shelf life and microbial contents of homemade soursop (*Annona muricata* L) fruit juice. *Biokemistri.* **25**(2), 31–38 (2013)
40. Goñi, I., Díaz-Rubio, M.E., Pérez-Jiménez, J., Saura-Calixto, F.: Towards an updated methodology for measurement of dietary fiber, including associated polyphenols, in food and beverages. *Food Res. Intern.* **42**(7), 840–846 (2009)
41. Jirovetz, L., Buchbauer, G., Ngassoum, M.B.: Essential oil compounds of the *Annona muricata* fresh fruit pulp from Cameroon. *Journ Agric. Food Chem.* **46**(9), 3719–3720 (1998)
42. Bicas, J.L., Molina, G., Dionisio, A.P., Barros, F.F.C., Wagner, R., Maróstica, M.R. Jr., Pastore, G.M.: Volatile constituents of exotic fruits from Brazil. *Food Res. Internat.* **44**(7), 1843–1855 (2011)
43. Schmidt, E.: Production of Essential Oils, in *Handbook of Essential Oils*, pp. 125–160. CRC (2020)
44. Roduan, M.R.M., Abd Hamid, R., Cheah, Y.K., Mohtarrudin, N.: Cytotoxicity, antitumor-promoting and antioxidant activities of *Annona muricata* in vitro. *Journ Herb. Med.* **15**, 100219 (2019)
45. Fasakin, A., Fehintola, E., Obijole, O., Oseni, O.: Compositional analyses of the seed of sour sop, *Annona muricata* L., as a potential animal feed. (2008)
46. Udoh, J., Alonge, A., Dairo, O.: Physical Characteristics of Soursop Seeds as Affected by Moisture Content. In 2017 ASABE Annual International Meeting. American Society of Agricultural and Biological Engineers (2017)
47. De Lima, M.C., Alves, R.: Soursop (*annona muricata* L.), in post-harvest biology and technology of tropical and subtropical fruits. Elsevier 363–392e (2011)
48. Mesquita, P.C., Rodrigues, L.G.G., Mazzutti, S., da Silva, M., Vitali, L., Lanza, M.: Intensified green-based extraction process

- as a circular economy approach to recover bioactive compounds from sour sop seeds (*Annona muricata* L.). *Food Chem: X*. **12**, 100164 (2021)
49. Aguilar-Hernández, G., García-Magaña, M.L., Vivar-Vera, M.Á., Sáyo-Ayerdi, S.G., Sánchez-Burgos, J.A., Morales-Castro, J., Anaya-Esparza, L.M., González, M.: Optimization of ultrasound-assisted extraction of phenolic compounds from *Annona muricata* by-products and pulp. *Molec*. **24**(5), 904 (2019)
 50. Jiménez, V.M., Gruschwitz, M., Schweiggert, R.M., Carle, R., Esquivel, P.: Identification of phenolic compounds in soursop (*Annona muricata*) pulp by high-performance liquid chromatography with diode array and electrospray ionization mass spectrometric detection. *Food Res. Internat*. **65**, 42–46 (2014)
 51. Ojo, O.A., Grant, S., Amanze, J.C., Oni, A.I., Ojo, A.B., Elebiyo, T.C., Obafemi, T.O., Ayokunle, D.I., Ogunlakin, A.D.: *Annona muricata* L. peel extract inhibits carbohydrate metabolizing enzymes and reduces pancreatic β -cells, inflammation, and apoptosis via upregulation of PI3K/AKT genes. *Plos One*. **17**(10), e0276984 (2022)
 52. Cárdenas, C., Torres-Vargas, J.A., Cárdenas-Valdivia, A., Jurado, N., Quesada, A.R., García-Caballero, M., Martínez-Poveda, B., Medina, M.: Non-targeted metabolomics characterization of *Annona muricata* leaf extracts with anti-angiogenic activity. *Biomed. Pharmacother*. **144**, 112263 (2021)
 53. Rubio-Melgarejo, A., Balois-Morales, R., Palomino-Hermosillo, Y.A., López-Guzmán, G.G., Ramírez-Ramírez, J.C., Cervantes-García, E., Villalobos-Rosario, B.J., Bautista-Rosales, P.U.: Phytochemical and antioxidant dynamics of the soursop fruit (*Annona muricata* L.) in response to *Colletotrichum* spp. *Journ Food Qual*. **2020**(1), 3180634 (2020)
 54. Berk, Z.: Food process engineering and technology. Academic press (2018)
 55. Jha, A.K., Sit, N.: Extraction of bioactive compounds from plant materials using combination of various novel methods: A review. *Trends Food Sci. Techno*. **119**, 579–591 (2022)
 56. Sasidharan, S., Chen, Y., Saravanan, D., Sundram, K., Latha, L.Y.: Extraction, isolation and characterization of bioactive compounds from plants' extracts. *Afr. Journ Tradit Complem Alternat Medic* **8**(1) (2011)
 57. Drosou, C., Kyriakopoulou, K., Bimpilas, A., Tsimogiannis, D., Krokida, M.: A comparative study on different extraction techniques to recover red grape pomace polyphenols from vinification byproducts. *Industr Crops Prod*. **75**, 141–149 (2015)
 58. Dominguez, H., Loret, E.P.: *Ulva lactuca*, a source of troubles and potential riches. *Mar. Drugs*. **17**(6), 357 (2019)
 59. Lefebvre, T., Destandau, E., Lesellier, E.: Selective extraction of bioactive compounds from plants using recent extraction techniques: A review. *Journ Chromatog A*. **1635**, 461770 (2021)
 60. Iyanda-Joel, W., Adegbite, O., Ajetunmobi, O., Chinedu, S., Iweala, E., Rotimi, S.: Phytochemical, antioxidant and mitochondrial permeability transition analysis of fruit skin ethanolic extract of *Annona muricata* Linn.(Soursop). *Toxicol. Let*. **2**(238), S248 (2015)
 61. Mason, T.J., Paniwnyk, L., Lorimer, J.: The uses of ultrasound in food technology. *Ultrason. Sonochem*. **3**(3), S253–S260 (1996)
 62. Chemat, F., Khan, M.K.: Applications of ultrasound in food technology: Processing, preservation and extraction. *Ultrason. Sonochem*. **18**(4), 813–835 (2011)
 63. Aguilar-Hernández, G., Vivar-Vera, M.D.Á., García-Magaña, M.L., González-Silva, N., Pérez-Larios, A., Montalvo-González, E.: Ultrasound-assisted extraction of total acetogenins from the soursop fruit by response surface methodology. *Molec*. **25**(5), 1139 (2020)
 64. Suzeta, A., Prasetyo, W., Nugroho, A., Rachman, R.: and Nursanto E.: Microwave-Assisted Extraction of Phenolic Compound from Soursop Peel (*Annona muricata* L.) and Its Antioxidant Potential and SPF Measurement. in Proceedings of the International Conference on Sustainable Engineering, Infrastructure and Development, ICO-SEID 23–24 November, Jakarta, Indonesia (2023). (2022)
 65. Xi, J.: Ultrahigh pressure extraction of bioactive compounds from plants—A review. *Crit. Rev. Food Sci. Nutr*. **57**(6), 1097–1106 (2017)
 66. Pereira, C.G., Meireles, M.A.A.: Supercritical fluid extraction of bioactive compounds: Fundamentals, applications and economic perspectives. *Food Bioproc Technol*. **3**, 340–372 (2010)
 67. Cottone, G., Giuffrida, S., Bettati, S., Bruno, S., Campanini, B., Marchetti, M., Abbruzzetti, S., Viappiani, C., Cupane, A., Mozzarelli, A., Ronda, L.: More than a confinement: Soft and hard enzyme entrapment modulates biological catalyst function. *Catalysts*. **9**(12), 1024 (2019)
 68. Kieliszek, M., Pobiega, K., Piwowarek, K., Kot, A.M.: Characteristics of the proteolytic enzymes produced by lactic acid bacteria. *Molecules*. **26**(7), 1858 (2021)
 69. Holland, C., Ryden, P., Edwards, C.H., Grundy, M.M.-L.: Plant cell walls: Impact on nutrient bioaccessibility and digestibility. *Foods*. **9**(2), 201 (2020)
 70. Chang, L.S., Karim, R., Sabo Mohammed, A., Mohd Ghazali, H.: Characterization of enzyme-liquefied soursop (*Annona muricata* L.) puree. *LWT*. **94**, 40–49 (2018)
 71. Idowu, A.T., Igiehon, O.O., Idowu, S., Olatunde, O.O., Benjakul, S.: Bioactivity potentials and general applications of fish protein hydrolysates. *Intern. Journ Pept. Res. Th*. **27**(1) (2021)
 72. Adefegha, S.A., Oyeleye, S.I., Obboh, G.: Distribution of phenolic contents, antidiabetic potentials, antihypertensive properties, and antioxidative effects of soursop (*Annona muricata* L.) fruit parts in vitro. *Biochem. Res. Internat* (2015)
 73. Idowu, A.T., Igiehon, O.O., Adekoya, A.E., Idowu, S.: Dates palm fruits: A review of their nutritional components, bioactivities and functional food applications. *AIMS Agricul Food*. **5**(4), 734–755 (2020)
 74. Kim, G.H., Kim, J.E., Rhie, S.J., Yoon, S.: The role of oxidative stress in neurodegenerative diseases. *Experim Neurobiol*. **24**(4), 325 (2015)
 75. Bartosz, G., Kołakowska, A.: Lipid Oxidation in Food Systems. Chemical, Biological, and Functional Aspects of Food Lipids. Eds. Z. Sikorski, A. Kołakowska, pp. 163–184. CRC, New York, USA (2010)
 76. Chib, A., Gupta, N., Bhat, A., Anjum, N., Yadav, G.: Role of antioxidants in food. *IJCS*. **8**(1), 2354–2361 (2020)
 77. Lee, W.Z., Chang, S.K., Khoo, H.E., Sia, C.M., Yim, H.S.: Influence of different extraction conditions on antioxidant properties of soursop Peel. *Acta Scientiarum Polonorum Technologia Aliment*. **15**(4), 419–428 (2016)
 78. Agu, K.C., Okolie, P.N.: Proximate composition, phytochemical analysis, and in vitro antioxidant potentials of extracts of *Annona muricata* (Soursop). *Food Sci. Nutri*. **5**(5), 1029–1036 (2017)
 79. Martínez-Mendoza, B., Peredo-Lovillo, A., Romero-Luna, H., Jiménez-Fernández, M.: Antioxidant and anti-inflammatory properties of yeasts fermented passion fruit and soursop pulps: A focus on bioactive volatile compounds profile. *Food Biosci*. **56**, 103112 (2023)
 80. Malviya, N., Jain, S., Malviya, S.: Antidiabetic potential of medicinal plants. *Acta Pol. Pharm*. **67**(2), 113–118 (2010)
 81. Nair, S.S., Kavrekar, V., Mishra, A.: In vitro studies on alpha amylase and alpha glucosidase inhibitory activities of selected plant extracts. *Europ Journ Experim Biol*. **3**(1), 128–132 (2013)
 82. Liaw, C.-C., Chang, F.-R., Lin, C.-Y., Chou, C.-J., Chiu, H.-F., Wu, M.-J., Wu, Y.-C.: New cytotoxic monoterahydrofuran annonaceous acetogenins from *Annona m uricata*. *Journ Nat. Prod*. **65**(4), 470–475 (2002)

83. Torres, M.P., Rachagani, S., Purohit, V., Pandey, P., Joshi, S., Moore, E.D., Johansson, S.L., Singh, P.K., Ganti, A.K., Batra, S.K.: Graviola: A novel promising natural-derived drug that inhibits tumorigenicity and metastasis of pancreatic cancer cells in vitro and in vivo through altering cell metabolism. *Cancer Let.* **323**(1), 29–40 (2012)
84. Kamala, P., Iyer, P.R.: Antiproliferative effects on tumor cells of the synthesized gold nanoparticles against Hep2 liver cancer cell line. *Egypt. Liver Journ.* **10**(1), 1–12 (2020)
85. Errayes, A.O., Abdussalam-Mohammed, W.: Darwish, review of phytochemical and medical applications of *Annona muricata* fruits. *Journ Chem. Rev.* **2**(1), 70–79 (2020)
86. Coria-Téllez, A.V., Montalvo-González, E., Yahia, E.M., Obledo-Vázquez, E.N.: *Annona muricata*: A comprehensive review on its traditional medicinal uses, phytochemicals, Pharmacological activities, mechanisms of action and toxicity. *Arab. Journ Chem.* **11**(5), 662–691 (2018)
87. Hajdu, Z., Hohmann, J.: An ethnopharmacological survey of the traditional medicine utilized in the community of porvenir. Bajo Paraguá Indian Reservation Bolivia *Journ Ethnopharmacol.* **139**(3), 838–857 (2012)
88. Betancur-Galvis, L., Saez, J., Granados, H., Salazar, A., Ossa, J.: Antitumor and antiviral activity of Colombian medicinal plant extracts. *Memórias Do Instituto Oswaldo Cruz.* **94**, 531–535 (1999)
89. Samuel, A.J.S.J., Kalusalingam, A., Chellappan, D.K., Gopinath, R., Radhamani, S., Husain, A., Muruganandham, V., Promwicht, P.: Ethnomedical survey of plants used by the Orang Asli in Kampung bawong, perak, West Malaysia. *Journ Ethnobiol. Ethnomed.* **6**(1), 1–6 (2010)
90. Alonso-Castro, A.J., Villarreal, M.L., Salazar-Olivo, L.A., Gomez-Sanchez, M., Dominguez, F., Garcia-Carranca, A.: Mexican medicinal plants used for cancer treatment: Pharmacological, phytochemical and ethnobotanical studies. *Journ Ethnopharmacol.* **133**(3), 945–972 (2011)
91. Atawodi, S.E.: Nigerian Foodstuffs with Prostate Cancer Chemopreventive Polyphenols. In *Infectious Agents and Cancer*. Springer (2011)
92. Pinto, A.D.Q., Cordeiro, M.C.R., De Andrade, S., Ferreira, F.R., Filgueiras, H.D.C., Alves, R., Kinpara, D.I.: *Annona Species*. Embrapa Cerrados-Livro científico (ALICE) (2005)
93. Ezurike, U.F., Prieto, J.M.: The use of plants in the traditional management of diabetes in nigeria: Pharmacological and toxicological considerations. *Journ Ethnopharmacol.* **155**(2), 857–924 (2014)
94. Kossouh, C., Moudachirou, M., Adjakidje, V., Chalchat, J.-C., Figuéredo, G.: Essential oil chemical composition of *Annona muricata* L. leaves from Benin. *Journ Essen Oil Res.* **19**(4), 307–309 (2007)
95. Ishola, I.O., Awodele, O., Olusayero, A.M., Ochieng, C.O.: Mechanisms of analgesic and anti-inflammatory properties of *Annona muricata* Linn.(Annonaceae) fruit extract in rodents. *Journ Medic Food.* **17**(12), 1375–1382 (2014)
96. Hasrat, J., De Bruyne, T., De Backer, J.-P., Vauquelin, G., Vlietinck, A.: Isoquinoline derivatives isolated from the fruit of *Annona muricata* as 5-HT_{1A} receptor agonists in rats: Unexploited antidepressive (lead) products. *Journ Pharm. Pharmac.* **49**(11), 1145–1149 (1997a)
97. Hasrat, J., Pieters, L., De Backer, J.-P., Vauquelin, G., Vlietinck, A.: Screening of medicinal plants from Suriname for 5-HT_{1A} ligands: Bioactive isoquinoline alkaloids from the fruit of *Annona muricata*. *Phytomed.* **4**(2), 133–140 (1997b)
98. Sun, S., Liu, J., Kadouh, H., Sun, X., Zhou, K.: Three new antiproliferative annonaceous acetogenins with mono-tetrahydrofuran ring from Graviola fruit (*Annona muricata*). *Bioorgan Medic Chem. Let.* **24**(12), 2773–2776 (2014)
99. Chang, F.-R., Liaw, C.-C., Lin, C.-Y., Chou, C.-J., Chiu, H.-F., Wu, Y.-C.: New adjacent bis-tetrahydrofuran annonaceous acetogenins from *Annona muricata*. *Planta Med.* **69**(03), 241–246 (2003)
100. Ragasa, C.Y., Soriano, G., Torres, O.B., Don, M.-J., Shen, C.-C.: Acetogenins from *Annona muricata*. *Pharmacog Journ.* **4**(32), 32–37 (2012)
101. Rabelo, S.V., Quintans, J.D.S.S., Costa, E.V., Da Silva Almeida, J.R.G., Júnior, L.J.Q.: *Annona* species (Annonaceae) oils. Essential oils in food preservation, flavor and safety: pp. 221–229 (2016)
102. Virgen-Cecea, L.J., Anaya-Esparza, L.M., Coria-Téllez, A.V., de Lourdes García-Magaña, M., García-Galindo, H.S., Yahia, E., Montalvo-González, E.: Evaluation of nutritional characteristics and bioactive compounds of soursop-yoghurt and soursop-frozen dessert. *Food Sci. Biotechn.* **28**(5), 1337–1347 (2019)
103. Olagunju, A.I., Sandewa, O.E.: Comparative physicochemical properties and antioxidant activity of dietary soursop milkshake. *Bever.* **4**(2), 38 (2018)
104. Zambrano, A., Raybaudi-Massilia, R., Arvelo, F., Sojo, F.: Cytotoxic and antioxidant properties in vitro of functional beverages based on blackberry (*Rubus glaucus* Benth) and soursop (*Annona muricata* L) pulps. *Funct. Foods Health Disease.* **8**(11), 531–547 (2018)
105. Akomolafe, S., Ajayi, O.: A comparative study on antioxidant properties, proximate and mineral compositions of the Peel and pulp of ripe *Annona muricata* (L.) fruit. *Internat Food Res. Journ* **22**(6) (2015)
106. Dias, P.I., Jayasooriya, M.N.: Enhancing the physiochemical and antioxidant properties of stirred yoghurt by incorporating soursop (*Annona Muricata*). *Intern. Journ Life Sci. Res.* **5**(1), 69–77 (2017)
107. Ademosun, A.O.: Glycemic properties of soursop-based ice cream enriched with Moringa leaf powder. *Foods Raw Mater.* **9**(2) (2021)
108. Senadeera, S., Prasanna, P., Jayawardana, N., Gunasekara, D., Senadeera, P., Chandrasekara, A.: Antioxidant, physicochemical, microbiological, and sensory properties of probiotic yoghurt incorporated with various *Annona* species pulp. *Heliyon.* **4**(11), e00955 (2018)
109. Santos, M.A.D.S., Ribeiro, P.V.L., Andrade, C.P., Machado, A.R.G., Souza, P.G.D., Kirsch, L.D.S.: Physicochemical and sensory analysis of craft beer made with soursop (*Annona muricata* L). *Acta Scientiarum Polonorum Technologia Aliment.* **20**(1) (2021)
110. Soltan, S.S., Shehata, M.: Antidiabetic and hypocholesterolemic effect of different types of vinegar in rats. *Life Sci. Journ.* **9**(4), 2141–2151 (2012)
111. Guzel-Seydim, Z., Seydim, A.: Antioxidant properties of strawberry vinegar. *Int. Journ Food Eng.* **5**(3) (2019)
112. Ho, C.W., Lazim, A., Fazry, S., Zaki, H., Massa, U.K.H., S., and, Lim, S.J.: Alcoholic fermentation of soursop (*Annona muricata*) juice via an alternative fermentation technique. *Journ Sci. Food Agricul.* **100**(3), 1012–1021 (2020)
113. Silva, E.K., Guimaraes, J.T., Costa, A.L.R., Cruz, A.G., Meireles, M.A.A.: Non-thermal processing of inulin-enriched soursop Whey beverage using supercritical carbon dioxide technology. *Journ Supercrit Fluids.* **154**, 104635 (2019)
114. De Souza, L., Villanova, J.R.C., De Souza, J.C.O., Maximino, T.D.S., R.C. and, Menini, L.: Vegetable fixed oils obtained from soursop agro-industrial waste: Extraction, characterization and preliminary evaluation of the functionality as pharmaceutical ingredients. *Environm Technol. Innovat.* **21**, 101379 (2021)
115. Martínez-Moreno, O.G., Anaya-Esparza, L.M., Sánchez-Burgos, J.A., Meza-Espinoza, L., Pérez-Larios, A., Bojorquez-Quintal, J.E., Montalvo-González, E.: Effect of vacuum-thermosonication

- on the inactivation of *Escherichia coli*, *Staphylococcus aureus*, polyphenol oxidase and the quality parameters of soursop puree. *Innovat Food Sci. Emerg. Technol.* **59**, 102255 (2020)
116. Yusof, S., Ibrahim, N.: Quality of soursop juice after pectinase enzyme treatment. *Food Chem.* **51**(1), 83–88 (1994)
117. Saavedra, A., Almendariz, D., Navarrete, D., Vernaza, M.G.: A new bread formulation based on a partial substitution of soursop residues flour through Mixolab and a process mixture design. *Food Sci. Technol.* (2021)
118. Tan, W.C., Muhialdin, B.J., Meor Hussin, A.S.: Influence of storage conditions on the quality, metabolites, and biological activity of soursop (*Annona muricata* L.) Kombucha. *Front. Microbiol.* **11**, 603481 (2020)
119. Ani, I., Ajuzie, N., Adeoye, B., Ngozi, E., Bassey, V.: Comparative nutritional quality and sensory properties of pure soursop juice and its blend with orange and/or pineapple. *GSJ* **7**(6) (2019)
120. Gyesi, J.N., Opoku, R., Borquaye, L.S.: Chemical composition, total phenolic content, and antioxidant activities of the essential oils of the leaves and fruit pulp of *Annona muricata* L.(Soursop) from Ghana. *Biochem. Res. Internat* (2019)
121. Amorati, R., Foti, M.C., Valgimigli, L.: Antioxidant activity of essential oils. *Journ Agricul Food Chem.* **61**(46), 10835–10847 (2013)
122. Huang, X., Lao, Y., Pan, Y., Chen, Y., Zhao, H., Gong, J., Xie, N., Mo, C.-H.: Synergistic antimicrobial effectiveness of plant essential oil and its application in seafood preservation: A review. *Molec.* **26**(2), 307 (2021)
123. Akacha, N.B., Gargouri, M.: Microbial and enzymatic technologies used for the production of natural aroma compounds: Synthesis, recovery modeling, and bioprocesses. *Food Bioprod. Proc.* **94**, 675–706 (2015)
124. Kowalska, H., Czajkowska, K., Cichowska, J., Lenart, A.: What's new in biopotential of fruit and vegetable by-products applied in the food processing industry. *Trends Food Sci. Technol.* **67**, 150–159 (2017)
125. Rodríguez-Roque, M.J., Sánchez-Vega, R., Pérez-Leal, R., Soto-Caballero, M.C., Salas-Salazar, N.A., Flores-Córdova, M.A. By-products from oilseed processing and their potential applications. *Oil and oilseed processing: opportunities and challenges*: pp. 183–201 (2021)

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