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Conventional and non-conventional phytochemical extraction of Bambara groundnut: A review

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Abstract Bambara groundnut (BGN) is a grain legume known for its nutritional value. However, its nutritional and nutraceutical potential associated with its phytochemical content is not fully tapped. This is probably due to the paucity of information on the various non-conventional extraction techniques used to extract the phytochemicals present in the different parts of the BGN. This review collated information on the conventional and non-conventional techniques applied in the extraction of phytochemicals from BGN. Among the techniques are ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical carbon dioxide extraction (SC-CO2), enzyme-assisted extraction (EAE), pulse electric field (PEF), subcritical water extraction (SWE), molecularly imprinted polymers (MIPs) and magnetic molecularly imprinted polymers (MMIP). Interestingly, researchers have regularly applied only UAE to extract phytochemicals from BGN. This could be the reason for the limited identification of some important low-molecular-weight phytochemicals that are in low concentration in BGN. A greater application of these techniques individually or in combination is necessary to promote the extraction of phytochemicals and reveal the potential of BGN.

Keywords: Bambara groundnut, Green extraction techniques, Microwave, Phytochemicals, Nutraceuticals

Introduction

Bambara groundnut (BGN) is a widely grown legume in Asia, and West and Central Africa. BGN is the third most important grain legume in sub-Saharan Africa due to its high nutritional value and commercial potential (Mohammed *et al.*, 2020). It is reported to contain 63% carbohydrates, 19% protein, and 6.5% oil, minerals, including calcium, iron, and potassium, vitamins, and a high fibre content (Temegne *et al.*, 2018; Chandra *et al.*, 2019). BGN is also a good source

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of nutraceuticals and other functional phytochemicals (Klompong and Benjakul, 2015). The phytochemicals in BGN have antimicrobial, anti-inflammatory, oestrogenic, antiallergic, antioxidant, and antitumor activities and some that stimulate the vascular system and inhibit some enzymes (Schwarz *et al*., 2018; Ferreira *et al*., 2019). The amount and diversity of phytochemicals extracted from plants depend on extraction techniques. Given the potential nutraceutical importance of BGN phytochemicals, researchers are required to use improved and novel extraction techniques with optimised variables to enhance quality and yield.

Recently, several promising green extraction techniques have been associated with reduced time and energy consumption have been introduced. They include ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical carbon dioxide (SC-CO2) extraction, enzyme-assisted extraction (EAE), pulse electric field (PEF), subcritical water extraction (SWE), molecularly imprinted polymers (MIPs) and magnetic molecularly imprinted polymers (MMIP) (El Kantar *et al*., 2018; Dassoff and Li, 2019). This review aims to gather information on the conventional and non-conventional (green extraction techniques) used in BGN. It also assesses the impact of the extraction techniques on the quantity, quality and nutraceutical potential of the phytochemicals.

Overview of Bambara groundnut

Bambara groundnut is an underutilised indigenous drought-tolerant legume that originated in West Africa and is now widely cultivated throughout sub-Saharan Africa (Hillocks *et al*., 2012). Over time, BGN cultivation has spread beyond its native region to other parts of Africa and some tropical regions around the world. Besides West Africa, it is grown in Uganda, Tanzania, Sudan, and Ghana. It is also grown in parts of Southeast Asia, including Indonesia and Malaysia (Cheng *et al*., 2019; Muhammad *et al*., 2020). BGN is the third most common legume after groundnut (*Arachis hypogea*) and cowpea (*Vigna unguiculata*) in Africa (Mkandawire, 2007; Khan *et al*., 2021). In addition to increasing food security, supporting pasture improvement, and generating income for subsistence farmers, this crop is also efficient in supporting sustainable land use.

BGN produces a respectable yield under environmental stress and has remarkable adaptability to a variety of growth conditions (Tan *et al*., 2020). Bambara groundnut is drought tolerant and can thrive in infertile soil and yet has high nutritional qualities (Bamshaiye *et al*., 2011). Furthermore, the crop can be grown productively in an area with an annual rainfall of less than 500 mm

(Bamshaiye *et al*., 2011). Seed emergence takes 5 to 21 days, and the plant thrives well in cold, moist highlands and well-drained rainforests (Khan *et al*., 2021). Flowering starts 30 to 55 days after planting and may continue until the plant dies (Brink and Belay, 2006). BGN is planted by small farmers in poor and degraded environments without irrigation or fertilisers (Mabhaudhi *et al*., 2013).

The uses and phytochemical composition of Bambara groundnut

BGN seeds contain fat, protein, fibre, and carbohydrates (Mahala and Mohammed, 2010; Khan *et al*., 2021). The plant is also rich in methionine, vitamins (B12, D) and minerals such as calcium, potassium, magnesium, phosphorus and iron (Amarteifio *et al*., 2006; Halimi *et al*., 2019). The seeds of BGN are used to produce low-fat yoghurt and vegetable milk (Mayes *et al*., 2013). Distinct parts of BGN plants are used to cure many diseases. Seeds are used to treat colon cancer and reduce the incidence of heart-related diseases in Africa (Koné *et al*., 2011). Fresh seeds are chewed and swallowed to treat nausea and vomiting, especially in pregnant women, as a remedy for morning sickness (Koné *et al*., 2011; Olanipekun *et al*., 2019). In Ghana, black seeds are chewed to alleviate swollen jaw diseases and treat skin rashes and diarrhoea (Majola *et al*., 2021; Okafor *et al*., 2021). In Senegal, BGN leaves are used to prepare a liquid that is used to treat epilepsy, infected wounds, and eyes, while the seed powder mixed with water is used to treat cataracts (Murevanhema and Jideani, 2013).

The nutritional and medicinal benefits of BGN depend on its phytochemical content (Unigwe *et al*., 2018; Melini and Melini, 2021). Harris *et al*. (2018) reported the presence of flavonoids and tannin in red and brown BGN hulls in South Africa. The flavonoids rutin and myricetin are present in brown BGN hulls, while the tannins chlorogenic acid and ellagic acid appear in red BGN hulls (Harris *et al*., 2018). An evaluation of the phytochemical constituent of BGN by Mubaiwa *et al*. (2019) found that raw and cooked red seeds of BGN are enriched with flavonoids, epicatechin and catechin. Polymerisation of catechin and epicatechin results in the formation of proanthocyanidins, which are referred to as condensed tannins and have been reported to have antioxidant, cardioprotective, anticancer, and neuroprotective effects (Rauf *et al*., 2019).

BGN also contains phenolic acids, saponins, sphingolipids, and fatty acids, in addition to flavonoid conjugates such as catechins, quercetins, kaempferol, and apigenin (Harris *et al*., 2018;). Phytic acid shows anticancer and antioxidant properties, suggesting its potential health-promoting properties (Mohan *et al*., 2015). Nyau *et al*. (2017a) showed that cooked BGN seeds contain phenolic compounds such as quinic acid, (E) GC-hexoside, catechin glucoside, medioresinol, p-coumaric acid, salicylic acid, caffeine derivatives, and catechin dimer. Whole and dehulled BGN seeds were found to contain phenolic acids, flavonoids, and lignan in varying amounts (amounts and phenolic level were higher in dark and whole seeds (Adedayo *et al*., 2021). Udeh *et al*. (2020) highlighted the presence of phenolic compounds (alkaloids, flavonoids, lignans, phenolic acids and tannins) in BGN that are known to treat some diseases. BGN contains more alkaloids than other legumes, and the hulls of different BGN landraces differ in alkaloid composition (Mbagwu *et al*., 2011). Given the beneficial roles of the extracted phytochemicals in BGN, it is necessary to evaluate the different extraction techniques for maximum extraction of phytochemicals.

Conventional extraction methods

Conventional (traditional) methods of phytochemical extraction are used to analyse, identify and quantify the various phytochemical compounds of plants (Rasul, 2018). Conventional extraction methods use solvents of varying polarity and require a long extraction time (Doughari, 2012). Commonly used solvents for extraction include methanol, ethanol, acetone, and water, while maceration, infusion, Soxhlet extraction, percolation, and steam and hydro distillation extraction are some of the conventional methods used to isolate these compounds.

Maceration

Maceration is one of the oldest and simplest extraction techniques (Jiang *et al*., 2021). and is considered a broad and low-cost way to extract natural products from plants (Rasul, 2018). The plant material is placed in a container and completely covered with a solvent, minimising contact with the air. In maceration, plant materials (fine or powdered) are soaked in a solvent for a minimum of three days, frequently agitated, and then left at room temperature (Handa, 2008). It involves softening and breaking the plant's cell walls to release its soluble phytochemicals (Azwanida, 2015). The mixture is then compressed and separated by filtration after a few days. The choice of solvents determines the type of compounds extracted from samples (Azwanida, 2015). Arya *et al*. (2012) compared different solvents in the extraction of phytochemicals from leaves of *Psidium guajava* L. using the maceration method. The authors observed that ethanol and hydroalcoholic solvents produced maximum yields of alkaloids, saponins, carbohydrates, tannins, and flavonoids compared to the other solvents, such as petroleum ether, chloroform, and water. Water was as efficient as ethanol, but alkaloids were not present in water extracts (Arya *et al*., 2012). This implied that bioactive molecules can be extracted from *P. guajava* more effectively with polar solvents (Azwanida, 2015).

Chutoprapat *et al*. (2020) evaluated the stimulation of anti-melanogenesis and collagen biosynthesis of BGN extracts (hulls and seeds) using maceration, infusion and Soxhlet extraction techniques. Methanol was used as a solvent for maceration and Soxhlet extraction. The extracted phytochemicals were variable. Maceration gave a higher yield from the seeds with the Soxhlet technique. The maceration technique produced the highest antioxidant, tyrosinase inhibition, and anti-melanogenesis activities from phytochemicals extracted from the hulls. Okafor *et al*. (2022) used maceration to assess phytochemicals in whole seeds and cotyledons of five varieties of BGN eaten in South Africa. The authors detected 26 and 24 phenolic compounds in the whole seeds and cotyledon, respectively, with 6 unidentified compounds. The presence of unidentified compounds suggests the need to employ more advanced extraction and detection techniques.

Infusions

The infusion process is like maceration, but extraction is carried out at a fixed temperature (normally higher than room temperature and up to 100°C) for a period and water is generally used as the extraction solvent (Verep *et al*., 2023). Traditionally, infusions were made using boiling water as the extraction solvent (Verep *et al*., 2023). According to Cittan *et al*. (2018), 95° C was found to be the optimal temperature to extract phenolic compounds from *Tilia cordata* fruits by infusions. Infusion was adopted by Chutoprapat *et al*. (2020) in the extraction of phytochemicals from BGN. Although the method did not produce very high yields from the seeds and hulls, the authors observed infusions produced a higher yield from the hull than maceration. It was also observed that the phytochemicals extracted from the seeds of BGN via infusion exhibited the highest stimulation of collagen biosynthesis.

Soxhlet extraction

Soxhlet extraction is a common method used to extract phytochemicals from plants (Lourenço *et al*., 2019). It is generally used as a reference for evaluating other solid-liquid extraction or new non-conventional extraction methods (Macías-Sánchez *et al*., 2010). In Soxhlet extraction, the plant material is placed in a thimble, which has perforations on the sides and bottom so that liquid drains through (Tiwari *et al*., 2013). A collection flask appears below the thimble, and a reflux condenser appears above it. When heat is applied to the flask, the solvent evaporates and moves to the condenser where condensation occurs. The solute is separated from the solvent by the distillation process. Fresh solvent is added to the flask containing the solute (Wang and Weller, 2006). This process is repeated until complete extraction of plant material is attained (Wang and Weller, 2006). In BGN, Chutoprapat *et al*. (2020) observed that Soxhlet extraction techniques gave the highest yield of extracts from both seeds and hulls, and the seed yielded more total phenolic and total flavonoid contents of the extracts from the seed compared to other methods of extraction. Ibraheem *et al*. (2023) evaluated the amino acid composition of BGN after $NaHCO_3$ treatment using the Soxhlet extraction technique. The authors were able to identify various amino acids such as lysine, methionine, and isoleucine, and observed the impact of treatment on the amino acid composition of BGN.

Steam and hydro-distillation

Steam and hydro-distillation are used to extract volatile components insoluble in water from various substances and to extract essential oils from plants (Prustry, 2022). These methods are widely used in the fragrance industry to extract essential oils (Seidel, 2006). In steam distillation, the steam is percolated through the plant material to dissolve the essential oil which is then separated from the water by decantation (Pushpangadan and George, 2012). For hydro-distillation, the only difference is that the plant material is submerged in the water, which is then heated until it boils (Azmir *et al*., 2013). Modifying the distillation time and temperature can optimise extraction. The diagrammatic representation of this extraction method is shown in Figure 1. These phytochemical extraction methods have not been used in BGN.

Percolation

The percolation technique is widely used to extract active ingredients in the preparation of tinctures (solution) and fluid extracts. The solid ingredients are moistened with an appropriate amount of solvent and allowed to stand for approximately 4 hours in a well-closed container called the percolator. More solvent is added to form a shallow layer above the mass, and the mixture is allowed to macerate in the closed percolator for 24 hours (Manousi *et al*., 2019) Thereafter the percolator outlet is opened and the liquid inside the percolator is allowed to drip slowly. Further solvent is added as required, until the percolate is approximately three-quarters of the required volume of the finished product (Handa, 2008). The process is repeated until the evaporated solvent in the percolator does not leave a residue (Rasul 2018). Little or no work has been done on BGN using this method of extraction. Table 1 provides a summary of the different conditions of the conventional methods used for phytochemical extractions. In addition, a summary of the advantages and limitations of the conventional methods of phytochemical extractions is provided in Table 2.

Figure 1. Conventional methods of phytochemical extractions

Table 1. Comparison of Various Conventional Extraction Methods and conditions for phytochemical extractions

Method	Solvent	Temperature	Pressure	Duration
Maceration	Water, aqueous and non-aqueous	Room	Atmospheric pressure	Long
Percolation	Water, aqueous and non-aqueous solvent	Room and occasionally under heat	Atmospheric pressure	Long
Decoction	Water	Under heat	Atmospheric pressure	Moderate
Soxhlet	Organic Solvents	Under heat	Atmospheric pressure	Long
Hydro distillation	Water	Under heat	Atmospheric pressure	Long

Table 2. Advantages and limitations of conventional phytochemical extraction techniques

Method	Advantages	Limitation	References
Maceration	Experienced operator not required. Energy saving process. Less soluble in solvent.	Slow and time-consuming. Require more solvent.	Ghanem *et al*. (2019) Azwanida. (2015)
Percolation	Requires less time than a maceration. Short time and more complete extraction. Extraction of thermolabile constituents can be possible.	Requires more solvent. Requires more time than soxhalation. Special attention should be paid to the particle size of the material and throughout the process.	Bitwell *et al*. (2023)
Decoction	Suitable for heat-stable compound extraction. Does not require expensive equipment. Easy to perform. Does not require a skilled operator.	Not suitable for the extraction of heat-sensitive constituents	Ghanem *et al*. (2019)
Soxhlet Extraction	quite efficient	This method risks the degradation of thermolabile compounds.	Bitwell *et al*. (2023)

Non-conventional methods of extraction

Ultrasound-assisted extraction (UAE)

The UAE technique is an advanced and non-conventional extraction method that is cost-effective, easy to apply, and more efficient (Fakhru-Nisa *et al*., 2019). The principle of UAE (Figure 2) is through sound wave propagation which is capable of cavitation creation in the solution. This leads to the destruction of the plant cell wall via the collapse of the cavitation under increased pressure, and the release of the phytochemicals into the solvent (Vernes *et al*., 2019). This method of extraction has been adopted in the extraction of phytochemicals in many food crops such as apple (Wang *et al*., 2018a), pomegranate (Sharayei *et al*. 2019), olives (Martínez-Patiño *et al*., 2019), and rice (Setyaningsih *et al*., 2019).

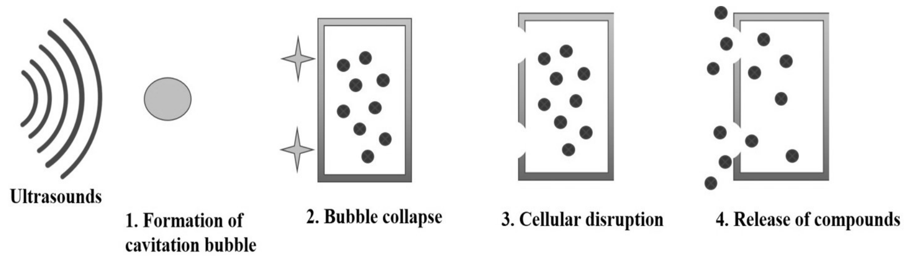

Figure 2. An overview of the operational principle of ultrasound-assisted extraction techniques. Source: Fakhru-Nisa *et al.* (2019)

Okafor *et al*. (2021) used the UAE method under the following conditions: solid/solvent ratio 1 (15g):10 (150 mL) g/mL for 30 minutes at 42 kHz in 70% methanol to determine the difference in the flavonoid compounds and tannins in the hulls of BGN. High concentrations of flavonoid compounds such as rutin (24.458 mg/g-1) and myricetin (1.800 mg/g-1) in brown hulls and tannins such as chlorogenic acid (0.115 mg/g-1) and ellagic acid (0.105 mg/g-1) in red hulls were detected. These findings improved our understanding of the colour formation of BGN seeds. Nyau *et al*. (2015a) also adopted the UAE method under the following conditions: solid/solvent ratio 1 (15):10 (150 mL) g/mL for 30 minutes at 40 kHz in 70% methanol to determine the antioxidant potential of red and brown seeded BGN landraces employing 1,1-diphenyl-2- picrylhydrazyl (DPPH) and Ferric Reducing Antioxidant Power (FRAP) *in vitro* assays. The UAE method was useful in differentiating the antioxidant properties of the two landraces based on *in vitro* DPPH and FRAP assays. The highest DPPH free radical scavenging activity and the total antioxidant power derived from FRAP were obtained in the brown-seeded landrace at EC50 of 347 $\mu g/mL^{-1}$ and 6 mmole Fe^{2+}/100 g DW, respectively. To elucidate the importance of the UAE method in the extraction of adequate phytochemicals from BGN and the differential impact of the antioxidant properties of the phytochemicals compared to the common bean, Nyau *et al*. (2017b) investigated the effect of cooking on the antioxidant activities and phenolic phytochemicals of red BGN and common beans by adopting this method under the following conditions: solid/solvent ratio 1 (15):10 (150 mL) g/mL for 30 minutes at 40 kHz in 70% methanol, as well as DPPH, FRAP and Folin Ciocalteu assays for phenolic phytochemical profiles. The results showed that cooking increased the antioxidant activities of both BGN and common bean with the common bean displaying higher free radical scavenging activity. Furthermore, several emergent phenolic compounds, mainly flavonoids, were revealed in both BGN and the common bean. Adebiyi *et al.* (2021) also employed UAE to identify diverse metabolites present in BGN and fermented BGN (called dawada). The authors identified varying groups of metabolites, including aldehydes, sterols, ketones, alcohols, nitrogen-containing compounds, furans, pyridines, acids, vitamins, fatty acids, sulphur-related compounds, esters, terpenes, and terpenoids, with variations in raw BGN and fermented BGN.

Results from previous studies showed that the UAE method is a promising tool for the extraction of vital phytochemicals of BGN that can be employed industrially in the food and medical industries. Compared to conventional methods of phytochemical extraction, UAE showed high reproducibility in a shorter period, accompanied by a higher yield of extracted phytochemicals, less energy input, easier manipulation, less solvent consumption and reduced temperature use (Vladic *et al*., 2019). However, its application and effectiveness are dependent on some factors that range from the origin of the extracting sample and its chemical composition, the selected solvent, time of extraction, temperature, and ultrasound power (Ramić *et al*., 2015). Hence, the appropriate selection of suitable process parameters coupled with other extraction techniques becomes necessary for the effective extraction of the required phytochemicals to improve yield. Some authors have reported that the coupling of UAE with other extraction methods such as microwave, hydro distillation, and supercritical CO_2 extraction improved phytochemical yields while consuming less energy and solvents (Dassoff and Li, 2019; Xing *et al*., 2019). These approaches are recommended for industrial and research purposes for the extraction of phytochemicals in BGN.

Microwave-assisted extraction (MAE)

MAE, a non-conventional phytochemical extraction technique, has been employed to extract diverse phytochemicals in various fields such as food science, agriculture, and environmental studies in pollutant detection and identification (Ramli *et al*., 2019; Yuan *et al*., 2019). It is considered a green extraction technique due to the following properties: energy savings, less solvent requirement, environmentally friendly, efficient, and robustness (Wang and Weller, 2006). Dhobi *et al*. (2009) indicated that the principle of this technique involves the heating effect of the microwave when applied to analyse a sample. This is true, especially for plant samples, which lead to the heating of samples' moisture and producing a corresponding pressure on the plant cell wall. This pressure will rupture the plant cell wall and release phytochemicals (Figure 3). Several factors such as the type and nature of the solvent used (Liu *et al*., 2017) and the power of the microwave (Nayak *et al*., 2015) affect the phytochemical yields of MAE. Kumoro and Hartati (2015) evaluated the effect of solvent concentration, solvent-material ratio, and microwave power on phytochemical yields of *Dioscorea hispida* Dennst (bitter yam) flour. The authors observed that all of the parameters mentioned above influenced the yield of the phytochemicals with the optimal phytochemical yields observed at 85% w/w ethanol with solvent volume: flour mass ratio of 12.5: 1, and microwave power of 100 W for 20 min. This implied that there is a need for adequate evaluation of the extraction conditions needed for optimal phytochemical yield concerning different crops.

MAE has been extensively used in the extraction of phytochemicals in some citrus plants (Fakhru-Nisa *et al*., 2019) to reveal their diverse phytochemicals. However, this technique has not been employed in the extraction of phytochemicals in BGN. Studies using this technique in BGN may be useful in the extraction of diverse phytochemicals and the identification of their nutraceutical properties.

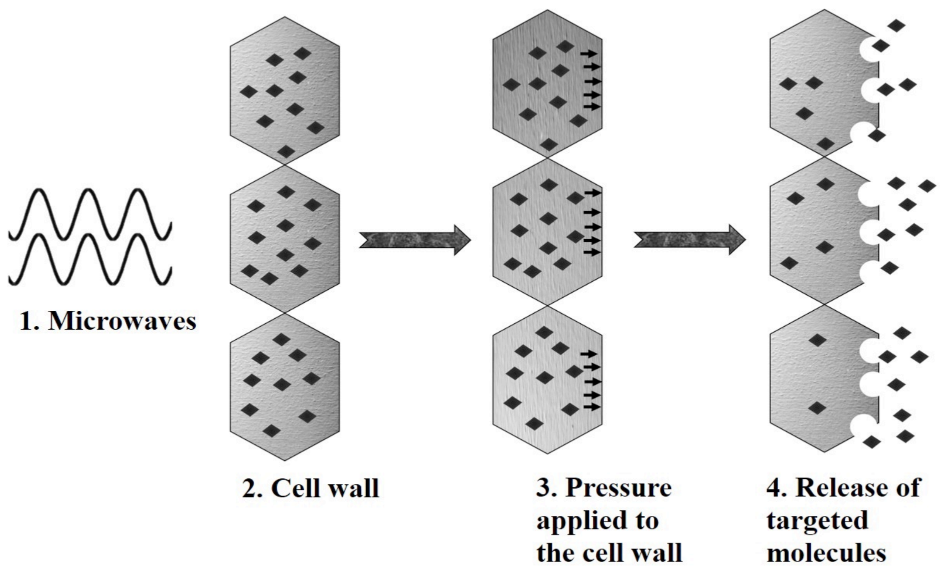

Figure 3. Operational principle of Microwave-assisted extraction techniques
Source: Fakhru- Nisa *et al*. (2019)

Other recommended extraction techniques for phytochemical extraction

Recently, several non-conventional extraction methods have been introduced and adopted in the extraction of diverse phytochemicals from various plants. Different phytochemicals in plants play different roles and can be used for different analytical research. Plants are rich with diverse phytochemicals that need to be identified and used for different purposes in the medical, research, and food industries and other fields of study. Hence, there is a need to adopt diverse extraction methods to fully harness the numerous phytochemicals present in plants, especially in BGN which has been underutilized and explored. Nonconvention extraction techniques such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical carbon dioxide extraction (SC-CO2), enzyme-assisted extraction (EAE), pulse electric field (PEF), subcritical water extraction (SWE), molecularly imprinted polymers (MIPs), and magnetic molecularly imprinted polymers (MMIPs) have been employed in the extraction of various phytochemicals in citrus plants (Fakhru-Nisa *et al*., 2019). Briefly, supercritical carbon dioxide (SC-CO_2) extraction involves the lowering of the CO_2 temperature in the heat exchanger due to the action of the recirculating chiller and glycol solution before the liquid CO_2 is pumped into the modifier. The modifier then performs the function of mixing the cosolvent with the liquid CO_2 which is being heated in the next heater exchanger at 31°C making the fluid super-critical. This leads to the dissolution of the targeted components from the reaction mixture and the extraction of the phytochemicals which are then collected in a fraction collector (Fakhru-Nisa *et al*., 2019).

The yield of phytochemicals in conventional extraction techniques has been reported to be limited or reduced by the components of the plant cell wall, such as cellulose, starch, and pectin, and the harshness of the treatment conditions of the technique (Acosta-Estrada *et al*., 2014; Dominiak *et al*., 2014). To avoid harsh treatment conditions accompanied by a high yield of phytochemicals, EAE is a promising extracting technique (Sasidharan *et al*., 2011). EAE employs the hydrolytic enzymatic approach (involving enzymes like cellulases, pectinases, and amylases) in the disruption of the cell wall and release of phytochemicals (Sheldon and van Pelt, 2013).

In a large-scale analysis of phytochemicals present in plants, a non-thermal extraction technique known as PEF has been used (Jaeger *et al*., 2012). This technique utilises the principle of electroporation and polarisation where the cell membrane of the plant cell is electroporated and polarised, leading to the disruption of the cell membrane and the release of the phytochemicals (Picart and Cheftel, 2003). This technique has been employed in the extraction of phytochemicals in citrus crops such as orange, pomelo, and lemon fruits (El Kantar *et al*., 2018). The result showed that this green extraction approach remarkably increased the quality and quantity of the extracted polyphenols.

Another eco-friendly, non-toxic, and cost-effective extraction technique is SWE. This technique uses water heated at a temperature between 100 and 374 ° C as the solvent for the extraction and a pressure high enough to maintain the water in the liquid state (Gbashi *et al*., 2017). Liew *et al*. (2018) observed that the use of this extraction method promoted the yield of low methoxyl pectins from *Citrus grandislosbeck* (pomelo) peels compared to conventional heating and sequential ultrasound-microwave-assisted acid extraction (UMAE) methods adopted by Methacanon *et al*. (2014) and Liew *et al*. (2016) that promoted the yield of high methoxyl pectin.

An extraction technique that employs the principle of affinity and specificity based on a memory of the functional group of a template molecule capable of attracting the needed polymers from the extracting sample known as MIPs has been applied to enhance the quantity and quality of extracted phytochemicals (Yin *et al*., 2015; Fan *et al*., 2016). This technique has been used by Miranda *et al*. (2016), Gao *et al*. (2016; 2017), and was found to be effective in the extraction of expected and desired phytochemicals. A modified technique involving the use of functionalised magnetic particles known as MMIP has been used in the extraction of phytochemicals such as hesperetin from *Citrus reticulatablanco* (Wang *et al*., 2018b). The authors recorded a higher yield of hesperetin using this technique compared to conventional extraction techniques.

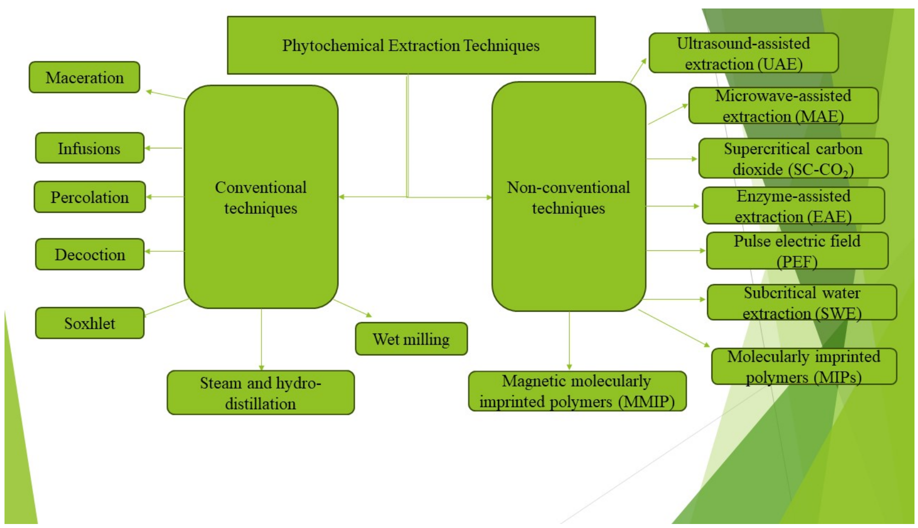

Figure 4. Conventional and non-conventional extraction techniques summarised in this study.

A call for application of advanced conventional and non-conventional phytochemical extraction in Bambara groundnut

BGN is grown for its seed in most rural areas in sub-Saharan Africa (Karunaratne *et al*., 2010). This crop has been ignored by most researchers despite its diverse nutrient composition (Mayes *et al*., 2013). This could be attributed to the paucity of knowledge about the phytochemical composition of the plant and its associated nutraceutical properties, including its antimicrobial and antioxidant potential. Recently, BGN has become the focus of research after the identification of the nutritional values of the plant and its phytochemical compositions. However, much research has not been done to identify, quantify, and elucidate the functional impact of the phytochemicals present in BGN using the green extraction techniques discussed above. Only UAE has been well applied by researchers in the identification of the phytochemicals present in BGN. Furthermore, the recent review done by Bitwell *et al*. (2023) on the conventional and non-conventional extraction techniques for phytochemicals in plants also showed few studies on the phytochemical extraction of BGN and the adoption of more advanced techniques. This may be the reason for the lack of knowledge about the various phytochemicals present in BGN and the functional impact of the phytochemicals. Figure 4 provides a summary of conventional and non-conventional techniques that can be further adopted in the elucidation of vital phytochemicals present in BGN.

Conclusion

Bambara groundnut is known for its nutritional and nutraceutical value and its ability to withstand drought. It has the potential to become a globally grown and utilised crop as part of food security in the coming decades. The ability of BGN to withstand adverse conditions could be associated with the phytochemical content of the plant. However, there has not been enough research employing green extraction techniques to identify numerous phytochemicals in BGN. Based on the collected information on various extraction techniques, the present review suggests further studies on the application of various green extraction techniques in BGN, and a comparison between the different techniques in terms of the type, quantity, and functional analysis of phytochemicals. Furthermore, a study on the differential phytochemical response of BGN in stress conditions and gene expression analysis to provide a better insight into the mechanisms of stress adaptation of BGN would provide valuable information.

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Conflicts of interest

The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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