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REVIEW ARTICLE

Tissue sampling, extraction methods, characterisation and applications of *Sclerocarya birrea* (marula) extracts: A review

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Abstract

Sclerocarya birrea (A. Rich.) Hochst. (marula), with its rich phytochemical content, is highly regarded in southern African communities. Characterisation studies on fruit, bark and other parts of the plant identified valuable phytochemicals like tannins, terpenes, flavonoids, alkaloids, oils, vitamins and many others which calls for unlimited research on marula applications. Though not usually very efficient, use of hand tools in the sampling of roots, bark, leaves and fruits is the most practised method of harvesting due to affordability in communities. Marula roots, leaves and barks are exploited mostly for their medicinal phytochemical content, fruits for their beverage and nutritional benefits while seeds are a source of food and oils used for skin care. Biodiesel, skin care products and alcoholic beverages production have been reported among commercial opportunities for *S. birrea*. Community based commercial activities involve vending wine, oils, jam and butter as a source of income. Other potential areas of application including paint additives, green corrosion inhibitors and surfactant manufacture among others, need research attention to scale up on *S. birrea* economic value and commercialisation. More sector specific organisations are required to coordinate knowledge and operations in the marula economy to widen the applications and adoption of marula products into the global markets. Future demand and interest on *S. birrea*-based products calls for sustainable exploitation and domestication of the plant as alternative conservation measures.

Keywords: food security; phytochemicals; *Sclerocarya birrea*; sustainable exploitation

Introduction

Sclerocarya birrea (A. Rich.) Hochst. (marula), is a freely and naturally growing deciduous plant which is native to many parts of sub-Saharan Africa. It favours savannah type of climate and is widely distributed from Senegal to Ethiopia in the northern part, further southward via central Africa to Kwazulu Natal in South Africa and to the southern west Africa in many other countries including Namibia and Botswana (1). Marula is a fast-growing deciduous plant with a single, circular cross-sectional trunk which, in mature plants can branch at about 3 to 4 m above the ground. The trunk will become thinner, finer branches and twigs which bear green, elliptically shaped and soft edged leaves (2) (Fig. 1). A fully grown marula plant height can have average height of 11 m or even up to 17 m and a stem diameter of 1 m depending on environmental factors (1, 3). The plant can grow from free falling seeds which can stay dormant in the soil for more than six months before they can germinate when there is sufficient rain (4). Fig. 1 shows a mature marula tree inside Botswana International University of Science and Technology, (BIUST) next to block 125.

Sclerocarya birrea has attracted a lot of research attention from various dimensions ranging from natural ecosystems in game parks where it is food for many herbivores like elephants, (5, 6) and a habitat for many small animals, to commercialization of its products like marula wines and skin care products (3, 7). In the history of southern African people, marula played an integral part of their culture, diet and tradition (8). The fruit has a sweet-sour juice and flesh that is often fermented to produce different forms of beverages. Extracts from other parts of the plant have antimicrobial, antioxidant, antidiarrheal, antidiabetic and anti-inflammatory activities making them useful in herbal medicine (9).

Increased research and demand for marula-based products can lead to potential threats from overharvesting of plant parts, hence the need for proper and adequate conservation strategies (10). Most exploited marula parts include the fruit for its pulp which is a rich source of vitamin C when eaten fresh or when prepared into jams and alcoholic beverages, the kernels, which are eaten as snacks for their high protein, fat and minerals content, marula oil from the nuts, which is used in cosmetics, food preparations and biodiesel production, roots and barks for their medicinal phytochemical content (11, 12). This review explores and compares the general applications of marula extracts, various methods of harvesting, sample treatment methods, extraction; characterization techniques and future prospects on the industrial and economic applications of *S. birrea*.

Fig. 1. Mature female *Sclerocarya birrea* tree.

An overview on tissue sampling techniques applicable to marula samples

In most parts of Africa, S. *birrea* is referred to as the tree of life because of its food security and medicinal value. Harvesting marula fruits, leaves, bark or cutting down of marula trees is controlled by communal and traditional leadership as a conservation measure to protect the plant from over exploitation (2). In some countries like South Africa, the recommended surface area of a piece of bark harvested for immediate use should not exceed 20 × 20 cm so that the scars are small enough for the tree to recover easily (2). Traditional methods of bark and root sampling for domestic and commercial use, though not as reliable, reproducible or well documented as those used in modern herbal medicine, ecology, agronomy and forestry research, they are still being used in communities, hence the need to regulate the harvesting of marula fruits and tree part (1). Use of approved eco-friendly sampling protocols when sampling marula roots, bark and any other parts should be enforced to minimise damage and improve plant population regeneration (13).

Destructive methods like targeting immature plants for harvesting, ring debarking and cutting the whole plant for the purpose of debarking or tissue sampling are not recommended (10). Ring barking is the complete removal of a wide circumference of the bark around the trunk of the tree which will disconnect its vascular system, resulting in the death of the stem and branches due to lack of water and nutrients (14). It can be done deliberately as a way of clearing land for other activities like farming or construction but is not suitable as a bark harvesting technique (15, 16). The male *S. birrea* plant is the recommended target for people harvesting firewood, bark and other tissues to secure the female plants which bear fruits (17). However, it's not always easy to distinguish between the males and female marula trees except during flowering and fruit bearing season, since they produce slightly different flowers.

Bark sampling

The bark which is the outer cover of the stems (Fig. 2), comprises of the inner bark which is living vascular tissue and the non-living outer bark. The inner bark transports nutrients from leaves and minerals in solution state along with water, while the outer bark prevents excessive water loss, protects the living tissues from insects, fungi and other microorganisms (18). Inner bark and outer bark are usually sampled together (Fig. 3). Harvesting methods are sometimes dependent on factors like sustainability, stem size and the after effects of the bark harvesting method (19). Post-harvest recovery and regeneration is affected by such factors like the amount of bark harvested, scar or wound depth, season of harvest, the amount of exudate released during sampling and the plant physiology (20). An investigation of the effect of wound size on the recovery of a plant from partial and total bark removal, showed that partial debarking up to 50 % circumference removal led to quick and successful recovery while 100 % bark removal caused larger wounds which took longer to recover (10). It is recommended to sample bark from a mature S. *birrea* stem (Fig. 2).

Fig. 2. Mature stem of *Sclerocarya birrea*.

Fig. 3. Bark sample of *Sclerocarya birrea*.

Root sampling

Roots serve key functional roles to plants including anchoring the plant as well as sequestering water and minerals from the soil. Biomass from roots is very difficult to generalise because its composition can be affected by many factors including spatial variability, accessibility, nature of soil, root morphology, anatomy and physiology (21, 22). All these factors contribute to root system and architectural heterogeneity resulting in variations in mineral and phytochemical composition (23). The most used method of root sampling is excavation and soil coring (21). Excavation involves using hand tools to dig pits to expose the roots. It can be ideal when sampling roots of very big plants like marula (Fig. 4), which can have most of its large roots radiating in all directions and downwards. In some cases, pits of dimensions 0.5 m^2 area to 1 m depth can be dug which can be a two-day labour for a single person, making it a laborious task (24).

On the other hand, soil coring method is done through forcibly driving a sharp polyvinyl chloride (PVC) or metal pipe of 5 cm diameter, into the ground using a rubber mallet or a powering motor to take out soil with small, fine and fibrous roots from up to 40 cm depth. Course, complex and larger root systems for bigger and mature trees like giant marula can be sampled using excavation (25) (Fig. 5). Coring bulky density soils and rocky soils, would require steel corers and motorised devices even to 1 m soil depths because PVC corers can break (24, 26). Unlike the manual type, the motorised power coring devise can cut through rock and larger roots, eliminating biases and challenges associated by compactness and presence of rocks in the soil during sampling (21). Fig. 4 shows excavated site under a marula tree and Fig. 5 shows roots sampled from an excavated site.

Fig. 4. Excavated site under *Sclerocarya birrea* tree.

Fig. 5. Marula roots from an excavated site.

Ground penetration radar (GPR) is another method which requires to be run prior to excavation. Ground penetration radar uses electromagnetic pulses, which are transmitted onto a surface and these pulses are reflected to the antenna which operates at a signal frequency of 450 MHz (25). Ground penetration radar obtains information on soil profiling and root architecture for plant root system as a computerised scan image (27). The technique has been applied in archaeology, civil engineering as a detection method for thick roots and buried services like cables and pipes, which may interfere with the construction processes or excavations currently under way (25, 28, 29). Ground penetration radar can show exactly where the roots are in the ground and excavation can be done precisely onto an area which has the root network (30). This can prevent unnecessary labour and damage to the root network.

Another excavation method involves a supersonic air stream (air spade) blown from a compressor at a pressure of 0.6 MPa and a speed of 0.8 $m^3 s^{-1}$ into the soil to expose the root system of a plant without damaging the roots (31). Both fine, course and larger roots can be accessed easily. However, the method can have limitations in very compact and rocky soils (21). Choice of root sampling method remains limited by factors like cost and availability of suitable equipment, purpose, aims for collecting the roots, quantities or volumes required, season of sampling, soil type and plant response to various methods of sampling (21, 23, 32). Despite the governing boards and communal authorities' recommendations on the use of eco-friendly and sustainable root harvesting methods, herbalists and researchers continue to use manual excavation as a more affordable method. However, use of hand tools in excavation may not allow plants to easily recover from resulting wounds and mechanical damage (33).

Sampling of twigs and branches

The most widely practised method of sampling twigs and fine branches is through pruning using hand tools like razor blades, pruning saws, pruning knives and pruning shears. Twigs of different sizes can be collected as illustrated in Fig. 6. Alternatively, drones called flying tree top samplers (FTTS) can be used to collect small diameter branches of range 0.8–1.6 cm. However, in dense canopy, it can be difficult for the drone to manoeuvre, set the gripper and the saw blade on position for sample collection (34). Use of hand tools like razor blades, knives and pruning shears remains the widely used twig sampling methods due to less costs. Fig. 6 shows *S. birrea* twigs sampled using pruning shears during midsummer time.

Fig. 6. Twig samples collected from *Sclerocarya birrea* tree.

The best time to prune deciduous trees like marula is in late winter when branches will be bare. However, to avoid effects of bleeding which may complicate regeneration, early summer pruning can do (35). Late summer pruning is often discouraged since it may affect flowering and next year fruit yield (36). Unlike bark and root sampling, quality pruning can improve the health, strength and aesthetic value of a tree (37). The strengths and drawbacks of different root, bark and twig sampling methods are given in Table 1.

Table 1. Advantages and disadvantages of different methods of bark, root and twig sampling

Marula part	Sampling methods	Comment	Advantages	Disadvantages	References
Bark	Use of pruning shears and razor blades	Ideal for small stems	Soft tender bark is harvested, less energy required	Small immature stems have less phytochemicals, young stems are destroyed	(19, 38)
	Use of a chisels and hammer	Ideal for large stems	Small pieces are removed giving smaller wounds, cheaper, good recovery rate	Requires more energy, wounds can result lead to attack by ants and microorganisms	(20, 35)
	Use of saws and axes	Larger stems can be ring debarked or partial debarked	Large sample size collected, fast sampling	Debarking can damage plant leading to poor recovery, large scars remain leading to infections	(10, 35, 39)
Roots	Excavation	Digging and removing soil to expose roots	Roots of different sizes can be sampled, large volume of biomass can be collected, reduce uncertainty and bias cause by soil properties	Laborious, root system is damaged	(21, 24)
	Soil coring	Sharpened pipes are driven into the soil to bring out soil containing the roots	Fine roots are sampled from small plants, less laborious	Limited to fine roots from small plants, not applicable to larger plant roots, difficult to apply on rocky and compact soils	(21, 25)
	Ground penetrating radar (GPR)	Scanned images of roots in ground prior to excavation	Locates root systems with high precision, large and small roots can be sampled, prevent unnecessary labour and damage to the root system	Very expensive to use, digging is still required	(25, 27, 28, 30, 31)
	Air spade	Blowing of the soil using air to expose roots	Less labour, fine, course and large roots can be accessed, less plant damage	Limited application in compact and rocky soils, cost of creating high pressure air jet	(21, 31)
Twigs	Flying tree top sampler (FTTS) / drone	Use of a drone to cut or collect branches and twigs	Less laborious, sample can be collected from different heights, very fast	Drones are expensive, small size of sample can be collected, it can be difficult to sample from dense canopy	(34, 40)
	Pruning saws, shears knives, razor	Use of cutting objects to collect twigs	Hand tools can be used carefully with minimum damage to the plant, make the plant look beautiful	More laborious, finer ends which bear fruits can be damaged, slow process	(34)

Sample treatment and extraction methods

Sample pre-treatment, purification and fractionation are common practices in laboratory-based research. Plant sample preparation processes for research involve several steps including prewashing, drying, grinding and sieving for homogenisation prior to extraction (41). After sample extraction and concentration of analytes, the ultimate processed sample is ready for an analytical step (42). Sampled raw plant material is often preserved under storage for several days and months during a chain of research activities to prevent depreciation of analyte content during storage and processing time (43). Measures should be taken during sample pre-treatment and purification processes since all these activities can affect the final extraction yield (42). The matrices of plant matter are a complex mixture of thousands of different phytochemicals with varying levels of both concentration and polarity. It is therefore very difficult to consider one single extraction method as the best or most suitable method for the extraction of the generality of phytochemical (44).

Sample storage and pre-treatment

Storage and treatment methods are very important factors which affects the stability of phytochemicals in the samples. Depreciation of phytochemical content of bark extracts from Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) after 8 weeks of storage has been reported (45). Some bark samples lose more water-soluble components during summer storage than in winter possibly due to higher temperatures and ultra-violet (UV) radiation, alongside the decomposing action of microorganisms and insects (43). Polyphenols, flavonoids and carotenoids can be decomposed through hot temperature pretreatment, but in some instances, hot extraction methods have been found to labilize these compounds and make them more available for extraction (46, 47). For instance, hot deoxygenated water at 40 to 150 °C was reported to have extracted 90 % of all phenols and polyphenols, implying that the effect of high temperatures on some phytochemicals can be insignificant (48). Most phytochemicals can remain stable if the sample is either freeze dried or air dried prior to milling or grinding instead of oven drying (49). Freeze dried samples can have an increased storage life of up to 30 years (41). However, the technique is both time-consuming and expensive when compared to oven or sun drying. The machinery and its supplies like liquid nitrogen and dry ice are not easily available (49).

Sample extraction methods and solvent effect

Extraction method selection is a very important step in laboratory analytical research where successful and efficient extraction of bioactive compounds are a pre-requisite (41). Extraction efficiency of the method, cost of instruments, availability of equipment and accessories, thermal degradability of targeted phytochemicals and nature of solvents used are critical factors (50). Some solvents and methods of extraction make certain compounds more labile than others. Treatment of the same sample with different solvents can result in different yields on total phenols, flavonoids and condensed tannins extracted from different marula tissues (Table 2). Methanol can extract more of total phenolic from the leaves when compared to hexane showing solvent effect on the success of extraction.

Different solvents can be used in extraction techniques like Soxhlet method, maceration, reflux, percolation, decoction and many others. Water, hexane, ethyl acetate, dichloromethane and methanol can be used together in Soxhlet extraction method (51). Soxhlet method has good percentage extract output and ability to extract phytochemicals of different polarity. However, when compared to maceration, it can give decreased yield of alkaloids and polyphenols and other thermally unstable bioactive compounds (52). In some extraction processes, fractionation can follow using different solvent extraction methods like liquid-liquid solvent extraction. A mixture of alcohols like methanol and ethanol in water is recommended for the extraction of a wide range of

Table 2. Effect of solvent on the extraction of total phenols, flavonoids and condensed tannins in *Sclerocarya birrea* extracts (51, 52)

Extracting solvent	Plant part	Total phenolics (mg GAE/100 g)	Flavonoids (mg QE/100 g)	Condensed tannins (%)
Methanol	Pulp	2.50	2.008	6.5
Methanol	Peel	2.20	0.90	4.9
Methanol	Pulp	505.83	33.90	NR
Acetone	Pulp	872.33	28.00	NR
Methanol	Leaves	304.50	NR	NR
Methanol	Bark	593.0	NR	NR
Hexane	Leaves	10.00	NR	NR
Ethyl acetate	Leaves	18.29	NR	NR
Water	Leaves	45.35	NR	NR
Hexane	Bark	48.43	NR	NR
Ethyl acetate	Bark	23.02	NR	NR
Water	Bark	90.33	NR	NR
	Oil cake	148.00	NR	NR
Methanol	Young stem	14.14	1.21	NR
Methanol	Leaves	13.95	0.47	NR
Hexane	Root	26.53	NR	NR

NR- Not reported, GAE- Gallic acid equivalence, QE- quercetin equivalence.

polar molecules when compared to non-polar ones (45, 53). A mixture of these solvents prepared in different proportions proves to be more effective than either one alone (45). A mixture of water and the nonpolar organic solvent like ether, dichloromethane, hexane etc. can also be used in isolating analytes from mixtures where extracted compounds are more soluble in the organic solvent and not in water for easier separation leaving the more polar in water (54).

Normal fractionation procedure involves treatment of sample extract with selected sets of solvents ranging from the least polar like hexane and chloroform, to medium polarity like dichloromethane and n-butanol and lastly the one with highest polarity such as water (54). As illustrated in Table 3, a comparative analysis of different extraction methods, their limitations and strengths are necessary to assist in the selection of appropriate extraction solvents and methods (55).

When selecting an extraction technique, an analyst must strike a balance between the strengths of the selected method and the results the method would provide. Factors like heat, temperature and light require particular attention especially when extracting thermolabile compounds (55). However, the most crucial factor to be considered remains the solvent which can dissolve out as much phytochemicals as possible (56).

Characterisation methods applicable to plant extracts

The complexity of *S. birrea* plant extract matrix caused by the existence of a wide range of phytochemicals makes separation, identification and characterisation processes to be a challenge. Different separation techniques such as thin-layer chromatography (TLC), column chromatography, flash chromatography, sephadex chromatography and high-performance liquid chromatography (HPLC), gas chromatography (GC) when coupled with appropriate detectors, separate and identify different compounds from complex extract mixtures (61–63). Common detectors include ultraviolet-visible spectrometer (UV-VIS), mass spectroscopy (MS) and diode array detector (DAD) (64). They are a means of identification of the separated components.

Thin layer chromatography analysis

Thin layer chromatography is used to identify and separate compounds in non-volatile extracts from medicinal plants, plant pigments and food additives (65). Sample solution in a volatile solvent is placed as spot on one pencil marked edge of a silicate or alumina coated plate. The plate is then placed in a developing chamber containing enough eluting solvent at a level just below the spot on the plate. The eluting solvent front will migrate up the plate, dragging the components of the extract at different rates. The components of the extract are then detected as separate spots on the plate. The retention factor (rf) of each spot can be calculated as a ratio of the distance moved by a component to the distance moved by the solvent as a means of detection (66).

Table 3. Different extraction methods, their strengths and weaknesses

Method	Solvent	Strengths	Weaknesses	References
Maceration	Water, aqueous and non-aqueous	Heat-stable chemicals can be extracted, easy to perform, no need for a professional operator, cheap equipment	Only highly soluble bioactive compounds can be extracted, takes a long time, more solvent used	(53, 55–58)
Percolation	Water, aqueous and non-aqueous	Process takes less time, thermolabile components can be extracted, more thorough extraction	More solvent used, skilled person needed, process requires more attention	(53, 55, 57)
Reflux extraction	Aqueous and non-aqueous	Conserve solvent, highly efficient, easy to use	Not suitable for thermolabile bioactive	(50, 53, 54)
Decoction	Water, aqueous and non-aqueous	Easy to perform, no special skill needed, cheap equipment	Not recommended for temperature sensitive bio actives	(53, 57, 58)
Soxhlet extraction	Non aqueous organic solvents	No need for filtration, moderate solvent volume, more thorough extraction	Sample agitation impossible, high chances of exposure to toxic solvents, not suitable for thermolabile bio actives	(53–55, 57)
Microwave assisted extraction	Water, aqueous and non-aqueous	Less solvent, less time, high solvent recovery	Non-polar solvents cannot be used, volatile solvents not permitted	(53, 55, 58)
Enzyme assisted extraction	Water, aqueous and non-aqueous	High extraction efficiency, wide range of phytochemicals can be extracted, nontoxic and non-flammable	Requires optimisation, highly affected by external factors like pH, presence of inhibiting ions, temperature, enzyme concentration etc.	(59, 60)
Ultrasound assisted extraction	Water, aqueous and non-aqueous	Reduced extraction time and solvent, thorough extraction and purification of bio actives	Ultrasonic radiation can affect phytochemical through creation of free radicals	(1)
Pulsed electric field extraction	Water, aqueous and non-aqueous	Thorough extraction in less time, non-thermal and suitable even for thermolabile bio actives	Cost and non-availability of equipment and accessories, bubbles produced cause nonuniformity and operational problems	(54, 56)
Supercritical fluid extraction	Carbon dioxide	Volatile components can be extracted and purified	Equipment costs are very high	(53–55)
Pressurised liquid extraction	Water, aqueous and non-aqueous	Less time consuming when compared to Soxhlet	Not suitable for thermolabile bio actives	(53, 54)

Column chromatography analysis

Column chromatography is a quantitative method used to separate and purify individual bioactive compounds by allowing sample solutions to elute through the column packed with silica gel (67). Columns can be simple glass pipes stuffed with appropriate stationary phase making them easier to prepare when compared to other chromatographic columns. This allows separation of components of the mixture forming moving bands or zones which can elute separately at the bottom of the column (66).

High performance liquid chromatography

High performance liquid chromatography is one of the most preferred analytical techniques for the isolation of natural product mixtures due to its ability to fingerprint components (64). High performance liquid chromatography-mass spectroscopy (HPLC-MS) was used to detect thirty-six compounds in the analysis of *S. birrea* bark, root and leaf extracts using HPLC as a separator and MS as a detector (68). The technique is the quickest and widely applied chromatographic technique for crude and complex plant extracts (69). High performance liquid chromatograph has been recommended by several researchers and authors as a suitable characterization tool for natural extracts because of its ability to give both quantitative and qualitative data about the sample which is a quality attribute of an analytical technique (69, 70).

Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy is a qualitative technique which provides specific information on the nature of chemical bonds and hence functional groups in the sample (71). Fourier transform infrared spectroscopy can analyse samples in gaseous, liquid and solid state (65). Gaining insight on the functional groups present in the sample can eventually lead to identification of the various categories of phytochemicals present and explanations of their observed properties (72).

Gas chromatography-mass spectrometry (GC-MS)

Gas chromatography - mass spectrometry uses GC as a separator and MS as a detector. It is a reliable means of analysis of complex extract mixtures using small volume of plant extracts per analysis (73, 74). Gas chromatography-mass spectrometry is an ideal technique for both qualitative and quantitative analysis for volatile and semi volatile components of mixtures (75). The technique was used to analyse *S. birrea* kernel oil (76). Identification of components of the mixture can be achieved through the interpretation of the retention indices and mass spectrum using the available database (77). Table 4 summarises some common analytical separation and identification techniques which are applicable to marula samples.

The choice of a characterisation technique remains guided by the availability of instruments, type of analytical data provided by the instrument, cost of instrument and accessories and sample preparation methods used. Most ideal practice is to use more than one technique in both qualitative and quantitative analysis so that the added strengths of the techniques can result in improved quality of results.

Health, economic significance and applications of marula tissue extracts

As highlighted earlier, nutritional, beverage and medicinal benefits of different parts of marula are well documented and their application is quite impressive. Other applications like biodiesel production, stock feed production, manufacture of jams and personal care products, though with less prominent research output, are gradually unveiling a wide range of consumer products from marula plant parts. Characterisation studies on *S. birrea* phytochemicals are in support of the breakthroughs made in several fields of application. Fig. 7 shows a summary of marula parts and their applications.

The future of *Sclerocarya birrea* plant and research focus

A marula economy is a possible future prospect which requires scaling up on the nutritional, pharmaceutical, cosmetics and biodiesel manufacture as well as exploring a limitless range of other possible applications of phytochemicals. Value chains need to be established in different fields of applications as a push towards large scale commercialisation of marula products. Manufacturing and processing industry is seriously affected by corrosion. Green corrosion inhibitors and paint additives manufacture using marula extracts, sounds like a worthwhile research endeavour, given the antioxidant properties of the extracts which can protect surfaces

Table 4. Common analytical separation and identification techniques applicable to marula plant extracts

Technique	Sample separation and identification	*Sclerocarya birrea* part applied	Strengths	Weaknesses	References
Thin layer chromatography (TLC)	Different rate of migration an alumina or silica stationary phase, characteristic rf values used for identification	Bark	Small sample volume can be analysed, wide application, inexpensive	Semi quantitative data obtained, mostly qualitative information obtained	(65, 66) (78)
Column chromatography	Differences in interaction of components with the mobile phase and stationary phase, requires a suitable detecting technique	Bark	Quantitative data obtained, separates and purify components, inexpensive glass column, disposability of spent stationary phase	Longer time of analysis, larger volume of solvent, low separation power	(67, 78)
High performance liquid chromatography (HPLC)	Differences in interaction of components with the mobile phase and stationary phase to give a chromatogram, requires a suitable detecting technique	Leaf Bark Root	Quantitative and qualitative data obtained, separates and quantify components, very fast analysis, robust, ability to finger print, versatile, high resolution	Expensive accessories	(63, 64, 68, 69)
Fourier transform-infrared spectroscopy (FTIR)	Interaction of sample components with infra-red radiation resulting in a spectrum, absorption peaks detect functional groups	Bark	Simple, rapid, non-destructive, sample analysed in any physical state	Not for quantitative analysis	(65, 71, 72, 78)
Gas chromatography mass spectrometry (GC -MS)	Different solubilities of components in the mobile phase to give a chromatogram, MS used to identify each component	Bark Kernel oil	Small sample required, produce both qualitative and quantitative, fast analysis, robust, highly efficient, ideal for separating complex mixtures of phytochemicals	Accessories can be expensive, sample preparation can be laborious	(73–78)

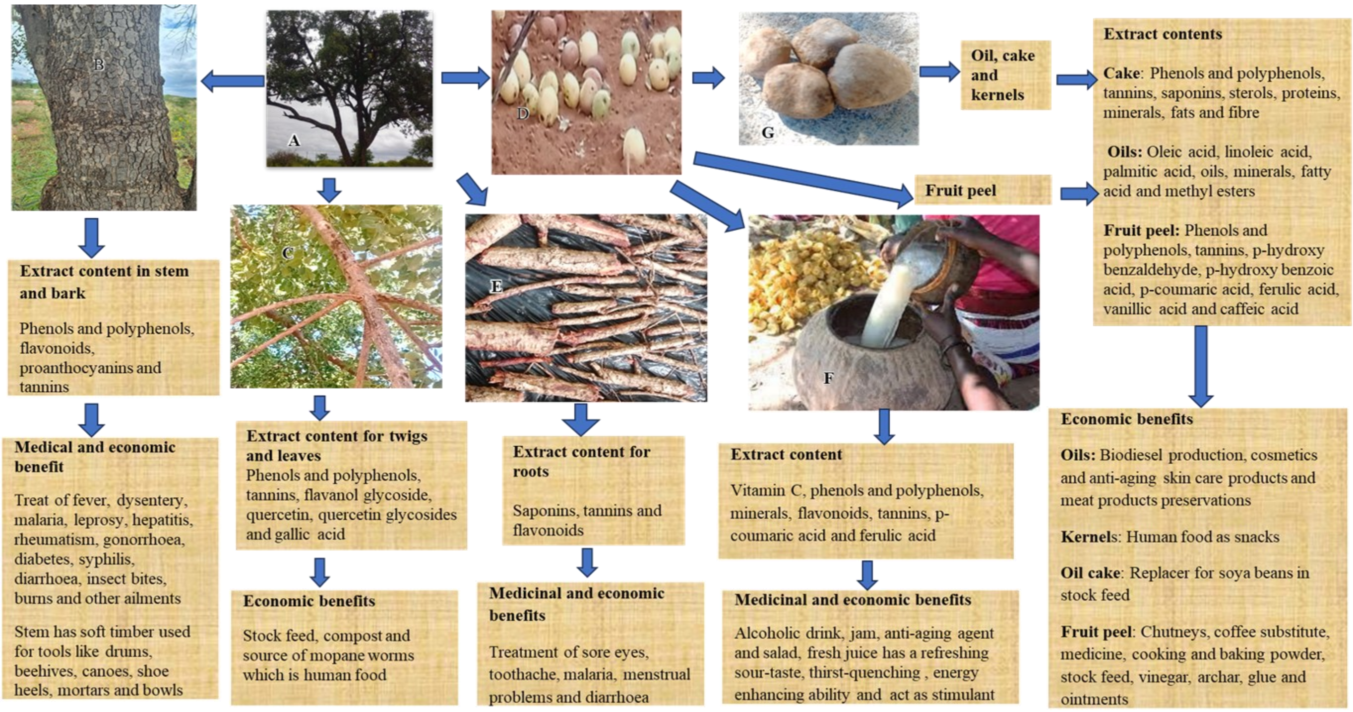

Fig. 7. Summary of *Sclerocarya birrea* (marula) tree parts, associated phytochemicals and their economic and medicinal benefits (11, 79, 80–87) (Photography F (79)). A: Marula tree; B: stem bark; C: twigs and leaves; D: Marula fruits; E: Marula roots; F: pulp; G: Marula nuts.

against degradation (80). An overview of the cost of corrosion and the use of other plant extracts as sources of green corrosion inhibitors can justify the application of marula in the field corrosion control and prevention.

Cost of corrosion

The approximate cost of corrosion worldwide, according to the National Association of Corrosion Engineers (NACE) increased to around USD 2.5 trillion in the year 2013 and is projected to keep on rising due to the current trends in industrial and technological advancements (88, 89). This cost accounts for about 3.4 % of world's Gross Domestic Product (GDP). Full implementation of the available corrosion remedies can significantly lower the costs by between 15 and 35 %, saving about US$375 and $875 billion annually (88). The current and ongoing industrial and technological advancements are being accompanied by the production of different types and concentrations of pollutants whose effects among others include corrosion and degradation of metallic structures (90).

Producing and designing corrosion resistant metal, alloy tools and structures is experiencing challenges due to the diversity and complexity of environmental conditions. For instance, stainless steel has been used in production of containers in the food industry due to its ability to maintain quality and purity of stored food. However, period of exposure to processing conditions in the food and beverage industry may compromise its immunity to the emergence of certain corrosion events. Exposure to pharmaceutical discharge effluents, fatty foods and chloride contamination may result in pitting corrosion on stainless steel surfaces (91). Other forms of steel and aluminium components which are part of the building materials for automobiles, piping, space craft and so forth, do corrode and lose value and strength. Since corrosion can be very difficult to design against or predict, it's imperative to continue researching on other methods of controlling corrosion especially green inhibitors. Rich phytochemical content makes marula a good option for research.

Sclerocarya birrea extracts and their potential applicability as green corrosion inhibitors

The motivation behind the use of plant extracts as corrosion inhibitors is not to substitute the existing control methods but to add on to the fight against corrosion. Inhibitors from plant extracts, commonly referred to as green corrosion inhibitors, are biodegradable, less toxic to humans and ecosystems, highly renewable and relatively cheaper which makes them potential options for the future corrosion inhibitors (92). Given the high phytochemical content, *S. birrea* plant extracts can be an *in situ* means of protecting stainless steel and other metals from corrosion especially when using acids, bases, or chlorates during cleaning (91). Plant extracts containing compounds with alkene, nitrogen, oxygen and sulphur-based moieties have good adsorptive abilities on metal surfaces, giving them better anti-corrosive properties (92). Examples include phenols, isoprene, limonene, alkaloids and many others. These compounds adhere using either chemisorption, physisorption or both on the metal surfaces to form a protective film which lowers the accessibility of corrosion active sites on the metal (89).

Substantial research work has been carried out on the efficacy of many plants as sources of green corrosion inhibitors (92). Characterization studies on *Euphorbia neriifolia*, a widely applied medicinal herb, showed the presence of saponins, terpenoids, flavonoids, tannins, alkaloids, among other phytochemicals during research on its corrosion inhibition ability (93). Same classes of compounds including flavonoids like rutin and apigenin, phenols like caffeic acid and p-coumaric acid were reported to be present in the extracts of *Ruta graveolens* which was used for corrosion inhibition experiments on stainless steel 304 (94). *Sclerocarya birrea* leaf ethanolic extract was also characterised using UV-VIS and GC-MS and a variety of phenols, flavonoids and alkaloids were found to be present (95). These findings are in support of marula extracts' potential in corrosion inhibition. Focus can also be directed towards using plant extracts as paint additives to investigate on their applicability in paint industry.

Prospects on increased marula product commercialisation and sustainable exploitation

Most community-based marula commercial activities are still at artisanal level where vendors sell kernels, beverages, pulp and other products without prospects for mechanisation (96). Communities will not realise the full economic benefit of the products due to the small-scale nature of business. A survey conducted in Beitbridge District in Zimbabwe, showed a reasonable income generated at household level through selling *S. birrea*-based products. Marula beer costs USD 2.00 per litre while marula oil can cost USD 30.00 per litre (7) (Table 5). This shows a greater economic potential of *S. birrea* if production is shifted from artisanal to mechanised methods.

Table 5. Average cost of *Sclerocarya birrea*-based products

Marula product	Quantity	Cost price (USD)
Marula oil	1 L	30
Marula jam	1 kg	5
Marula butter	1 kg	4
Marula nuts	1 kg	3
Marula beer	1 L	2
Marula fresh fruits	1 kg	0.50

However, with the advent of current research focus, more mechanised production and large-scale economic activities will be realised soon and conservation of *S. birrea* becomes paramount. Surveys and research have been carried out and are still being carried out on strategies to establish and sustain marula-based agroforests through its domestication (97), mapping and predicting at a global scale, suitable areas where *S. birrea* can be cultivated, conserved and used to restore drylands (98). The success of dryland reclamation using marula trees is based on the tree's ability to adapt well to semi-arid locations and drought-prone areas (7). Such land reclamation programs are highly recommended, in establishing an abundant source of marula-based phytochemicals for the creation of large commercial investments and manufacturing applications.

Sclerocarya birrea sectors and accessing of global markets

A marula economy in which marula biomolecules are processed into commercial products for global markets, can be accelerated by establishing sectors which specialise in specific areas of application. Such sectors should include people and organisations in various marula value chains including harvesting communities, cooperatives, product developers, trade associations, funders, product exporters and retailers (99). These sectors give a coordinated support to local producers and product manufacturers with information on international market regulations and standards, production expansion opportunities and how to access international markets. One successful sector project, access and benefit sharing (ABS) compliant Biotrade in South(ern) Africa (ABioSA) project has been established in southern Africa and has done a lot on regularising nutritional ingredients and consumer products from *S. birrea* fruit pulp, seeds and oil for international markets including European Union (EU). The project was established to support the production and commercialisation of products from indigenous plants in a way which sustains livelihoods and the environment (99). More marula sector organisations should be established to coordinate other value chains, not limited to nutritional, skin care and medicinal products but also to engineering fields like biodiesel manufacturing and corrosion inhibition.

Conclusion

Marula tree has always been valued in many African societies for its uses and applications in food and beverages, pharmaceuticals and herbal medicine due to its rich phytochemical composition. Other topical research issue includes among others corrosion prevention, paint additive and industrial surfactants production with particular focus on compatibility with existing products. There is need for more cheaper, less toxic, locally available, renewable, eco-friendly methods and sustainable methods of managing corrosion. *Sclerocarya birrea* plant extracts are a plausible and promising option for these potential applications. A marula economy is possible if sectors can be established for coordinating commercialisation and research activities across marula product value chains. The tree has been exploited largely at an artisanal level in the communities, which limits its economic potential. However reasonable household income is generated from vending of marula beer, oil, jams, kernels and other products. Mechanised exploitation of the plant and global marketing accessibility is being pushed forward through the establishment of proper value chains and marula sector organisations. Marula sampling, sample extraction, storage and analysis methods are dependent on cost and availability of resources. Marula domestication and land reclamation using *S. birrea* tree are a highly commendable initiative which ensures a stable renewable source for *S. birrea* phytochemicals and sustainability exploitation of the plant.

Authors' contributions

MM carried out conceptualisation, drafting, sequencing and alignment of the manuscript. BAO supervised the writing and compilation, reviewed and corrected the manuscript. VKM read, revised the manuscript and supervised the drafting of the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

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