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REVIEW

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Marama bean [*Tylosema esculentum* (Burch.) A. Schreib.]: an indigenous plant with potential for food, nutrition, and economic sustainability

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Developing countries need to explore undervalued indigenous plants to fully enhance their food and nutrition security, health, and economic viability. This review explores the nutritional, phytochemical, and economic potential of marama bean (*Tylosema esculentum*, Fabaceae), a non-nodulating indigenous legume that can be cultivated in and is well-adapted to dry or low moisture conditions. Marama bean is popularly referred to as 'green gold' due to the considerable value derived from its above ground and underground organs. The seeds have nutritional value comparable to legumes such as groundnut and soybean. In addition, the seeds are a rich source of phytochemicals such as phenolic acids, phytosterols, flavonoids, behenic acid and griffonilide while carbohydrates are abundant in the tubers. Based on the existing literature, marama bean remains poorly explored, mainly anecdotal with limited scientific evidence available to support its nutritional and medicinal uses as well as economic benefits. This has been ascribed to a shortage of clear research goals and limited resources specifically directed to this underutilized indigenous plant. From an economic and commercial perspective, the high phytochemical content suggests the possibility of developing a functional health drink and associated value-added products. However, efficient cultivation protocols for marama bean, especially to ensure the sustainable supply of the plant material, remain crucial. Furthermore, novel approaches, especially the use of molecular techniques that can facilitate rapid selection of desired traits in marama, are recommended. These anticipated improved agronomical traits will enhance the commercial and economical potential of marama and also contribute to rural–urban food-nutrition sustainability globally.

1. Introduction

Legumes are excellent crops for global food and nutrition security, serving as protein, fibre, vitamin and mineral sources.[1,2] In developing countries where protein–energy malnutrition is often a major nutritional problem, the importance of consuming legumes as a less expensive alternative cannot be over-emphasized.[3,4] Indigenous legumes have the potential to increase the protein content of diets in developing countries.[5,6] However, many underutilized indigenous legumes remain undomesticated thereby limiting their potential nutritional and economic value.[7,8] Exploring the domestication and cultivation of "underutilized plants" including marama beans (*Tylosema esculentum* (Burch.) A. Schreib) can ameliorate the present dependence on a few legumes that can pose agronomic, nutritional, economic and ecological threats. The success of exploring indigenous plants for nutritional and commercial value lies in their effective domestication, cultivation, preservation and conservation.[9–11]

Agronomic conditions, nutritional composition, and molecular characteristics need to be determined for marama breeding and domestication.[12] Furthermore, exploring the underutilized marama bean for nutritional, health and economic benefits may contribute to food security and sustainable livelihoods in Africa.[13] Therefore, a detailed scientific study of marama bean, its nutrients and phytochemical constituents, and breeding approaches for plant improvement as well as environmental sustainability is urgently needed. This review provides a critical appraisal of the botany, taxonomic description, nutritional and phytochemical characteristics and biological properties of marama bean. In addition, the economic prospects of marama bean for household food and nutrition security, income and value addition opportunities are explored.

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2. Botanical, phenotypic and taxonomic description of marama bean

Marama bean is a perennial legume, a member of the Fabaceae, and its common names include Braaiboontjie Marumama, Gembok beans, Gemsbokboontjies, Muraki, Tamani berry and Morama. The plant grows sporadically during summer and flourishes in soils with little organic matter, nitrogen, and phosphorus at temperatures of 28–37 °C. In addition, it needs sunshine for 3 h on either side of midday, *ca.* 2000 μmol m^{-2} s^{-1} light intensity. As a "drought tolerant" plant, it has a unique role in the agroecology where it is cultivated.[12] The stem grows as a vine up to 3 m in length at maturity (Fig. 1a and b). The leaves are bi-lobed and soft/succulent when young but become thick or leathery and greyish at maturity (Fig. 1a). The flowers are approximately 25 mm long, borne in a raceme and yellowish in colour. It has pods that are hardy in nature with 1–3 seeds per pod (Fig. 1b). The seeds in the pods are oval-shaped and tough, and have reddish-brown-black coloration (Fig. 1c).

3. Origin, geographical distribution and the major growing areas of marama bean

Marama bean, also known as "the green gold" is considered a native of the Kalahari Desert of South Africa.[14] It grows naturally in countries such as Namibia and Botswana. The marama bean is undergoing experimental cultivation in Australia, Israel, Kenya and the United States of America (Fig. 2A).[15] This plant is also sparingly cultivated in Mozambique and Zambia. Marama bean is found in the North West, Northern Cape, Limpopo and Gauteng Provinces of South Africa (Fig. 2B), according to the National Department of Agriculture, Forestry and Fisheries.[16]

4. Nutritional and phytochemical content in marama bean

Marama is a major source of diverse phytochemical and nutritional compounds. The chemical profile of marama bean and its comparative analysis with other protein rich legumes have been recently reported in the literature.[17] Its nutritional and phytochemical content has a diverse range of uses in industries involved in functional foods, pharmaceuticals and nutraceuticals.[18]

4.1. Nutritional composition of marama bean

The matured seeds of marama bean are prepared in different ways such as roasting, boiling or grinding.[19] In addition, the seeds are used for producing oil, butter and porridge. Generally, the seeds are well-preserved when they remain unopened in their pods due to their hard outer cover. Heated and unheated

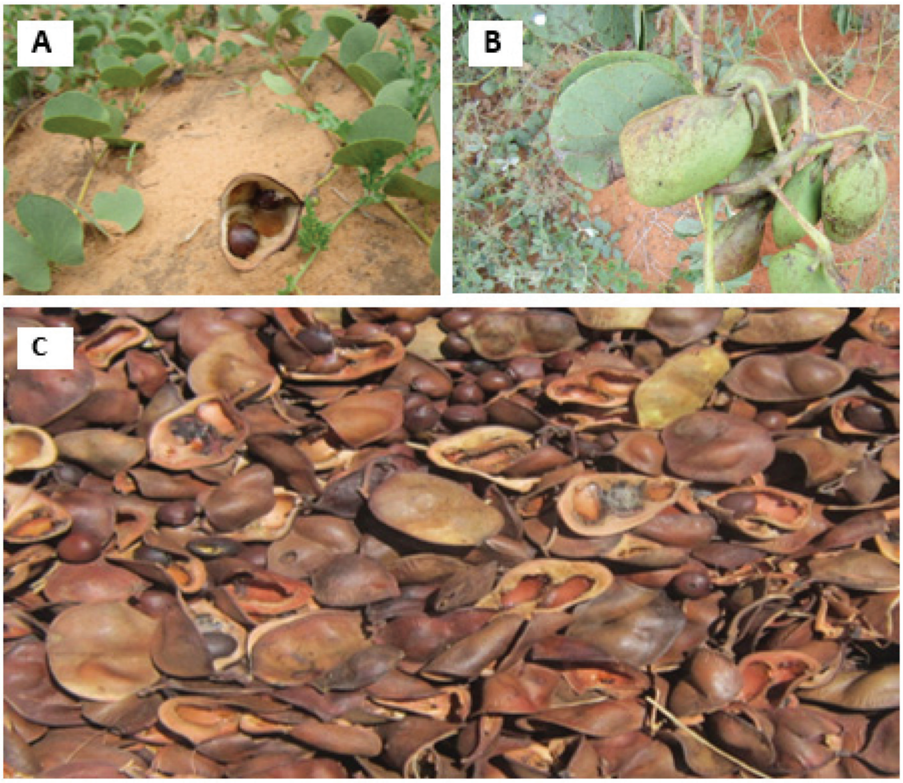


Fig. 1 Morphology of marama bean (*Tylosema esculentum*): (A) a typical growing marama bean vine, (B) immature pods and (C) harvested dry seeds.

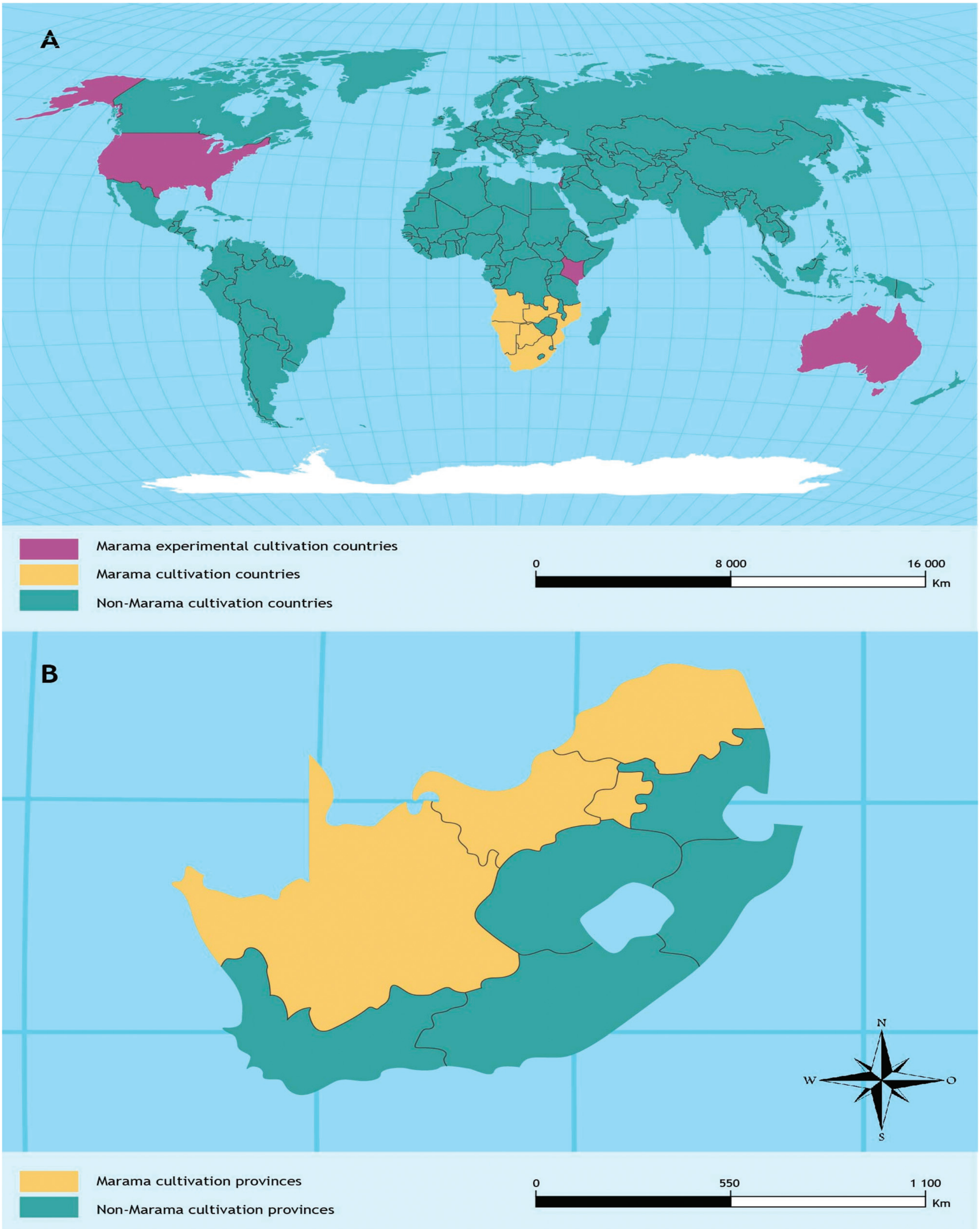


Fig. 2 Geographical locations for marama bean cultivation (A) globally and (B) in South Africa.[15,16]

marama beans can be made into flour for food.[20] Similarly, marama bean milk, a nutritious beverage, resembles soymilk or dairy milk and has other refreshing possibilities.[21,22] Marama bean has macronutrients that are required in human diet, particularly protein, dietary fibre and healthy fats. The micronutrient (*e.g.* vitamins and minerals) content is highlighted in Table 1. Marama beans are rich in calcium (241 mg per 100 g), which is essential for human bones and teeth.[23]

The beans are a source of magnesium (274.5 mg per 100 g), which serves as a catalyst in biochemical and physiological processes.[25] According to Müseler and Schönfeldt,[23] marama bean contains iron (3.95 mg per 100 g), which is essential for the prevention of anaemia. In addition, marama bean contains zinc (6.2 mg per 100 g), which is useful for protein metabolism and growth. The deficiencies of these micronutrients are common among the rural populations of developing countries and are often caused by the lack of financial means to acquire and consume sufficient quantities of red meat, chicken, fish, fruit, and vegetables.[26]

The underground part of marama produces a tuber that is larger in size and more nutritious than common potatoes, yams and sugar beets which are common staple tubers.[27] The tuber is edible raw, boiled, or roasted but needs to be harvested at a younger stage of the plant's growth (*i.e.* 1 or 2 years old), when it is nutritious and succulent for consumption.[25] The tuber becomes fibrous and bitter to taste, but could serve as an important water reservoir for farmers, hunters and animals in times of emergency. This tuber within a few years of maturity can attain a mass of 12 kg with 90% water content on average.[25] Furthermore, the tubers are rich in carbohydrate (11.85 g). Young tubers of marama have a good, succulent, and sweet taste and their texture has been described as similar to that of artichoke (*Cynara cardunculus* var. *scolymus*). Marama tubers are reddish when dried and edible.[28] In addition, the immature and mature stems are edible and used for making soup. It is also regarded as particularly good fodder for livestock.[25]

Table 1 Comparison of the nutrient composition of marama bean (per 100 g dry matter) with that of soybean and groundnut '—' = not done

Class	Nutrient	Marama bean[23]	Soybean[24]	Groundnut[24]
Proximate	Ash (%)	3.19	4.50	3.80
	Dry matter (%)	96.22	92	95
	Fat (%)	40.06	25	50
	Moisture (%)	2.67	7	9
	Non-structured carbohydrates (g)	11.85	15	20
	Protein (%)	34.71	45	25
Minerals	Calcium (mg)	241	—	—
	Chromium (mg)	0.06	—	—
	Copper (mg)	1.04	—	—
	Iodine (mg)	0.06	—	—
	Iron (mg)	3.95	—	—
	Magnesium (mg)	274.5	—	—
	Zinc (mg)	6.2	—	—
Vitamins	Vitamin B_{12} (mg)	0.043	—	—
	Vitamin B_6 (mg)	1.56	—	—

4.2. Amino acids in marama bean and their functions

Marama beans contain amino acids such as alanine, arginine, aspartic, cysteine, isoleucine and leucine (Table 2). These compounds are building blocks of proteins and play many critical roles in the human body.[23] Amino acids regulate multiple processes with regard to gene expression and modulate proteins that mediate messenger RNA (mRNA) translation.[29] Essential amino acid deficiencies lead to a lack of protein synthesis. As shown in Table 3, the major amino acids (composition per 100 g) in marama seed are glumatic acid, aspartic acid and tyrosine acid.[20,30,31]

4.3. Fatty acids in marama bean and their functions

Marama bean oil is yellow (*i.e.* golden yellow). The principal fatty acids are: arachidic (3%), essential for synthesis of various hormones, such as prostaglandins, thromboxanes, and leukotrienes;[33] linoleic (19–26%), an important constituent of neuronal membrane phospholipids and a precursor of prostaglandins;[34] oleic (48–49%), modifies plasma lipid and lipoprotein concentrations, inhibits coagulation, improves glucose homeostasis, and attenuates inflammation;[35] stearic (7–10%), does not increase atherosclerosis risk and is associated with reduced blood pressure and improved heart function;[36] and palmitic acid (12–14%), has shown anti-inflammatory and lipid lowering effects linked to the prevention of metabolic syndrome, cardiovascular disease and insulin resistance associated with diabetes and obesity.[37] As reported by van der Maesen,[28] 100 g dry weight of defatted marama bean seed meal contains 194 kJ (*i.e.* 46 kcal) of energy, 55 g of protein, 13 g of available starch and 1.6 g of fibre. As shown in Table 3, marama bean contains high levels of oleic acid (42.16% of total fatty acids) and linoleic acid (31.11% of total fatty acids). Furthermore, long-chain unsaturated fats are healthier than saturated fats which have been reported to cause astrocyte activation and brain inflammation associated with neuropathy in metabolic disease such as obesity.[38] The fatty acids present in marama bean demonstrate several health benefits.[23,31]

4.4. Phytochemicals in marama bean and their functions

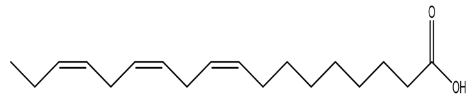
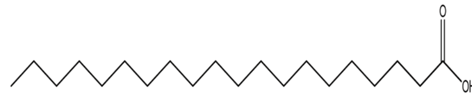
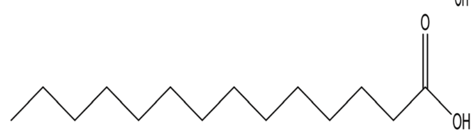
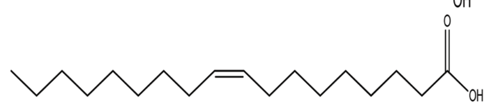
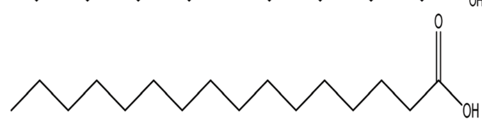
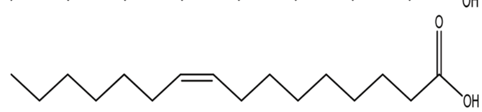
Marama bean is a potential source of diverse phytochemicals including phenolics, flavonoids, saponins and phytosterols (Table 4 and Fig. 3). These phytochemicals are capable of enhancing the immune system and protecting the body against pathogens.[42,43] The biological activities of different parts of marama in mitigating the risk of non-communicable diseases, diabetes and some cancers have been explored.[39] According to Jackson *et al.* and Bousquet,[22,44] marama is effective against gastroenteritis by inhibiting enteric bacterial and viral pathogens, fights drug resistant infections and reduces inflammation. Furthermore, Chingwaru *et al.*[45] identified that marama bean has anti-microbial (anti-bacterial) activities. Marama bean seed coat and cotyledon polyphenolic fractions have relatively high anti-bacterial and anti-fungal activities, implying their possible use as new and potent anti-microbial drugs.[46] In addition, the cotyledon and seed

Table 2 Overview of amino acids and their functions in nutrition and metabolism as well as the composition in marama bean (per 100 g dry matter) '—' = not available

Amino acid	IUPAC name	Function in nutrition and precursor	Composition per 100 g dry matter[20,31]	
Arginine	(2*S*)-2-Amino-5-(diaminomethylideneamino) pentanoic acid	Antioxidant; regulates hormone secretion; ammonia detoxification; gene expression; immune function; N_2 reservoir; methylation of proteins; deamination (formation of citrulline) of proteins. Its metabolism produces nitric oxide (NO) a signaling molecule; regulates nutrient metabolism, hemodynamics, angiogenesis, spermatogenesis, embryogenesis, fertility, immune function, hormone secretion, wound healing, neurotransmission, mitochondrial biogenesis[32]	6.3	7.3
Cysteine	(2*R*)-2-Amino-3-sulfanylpropanoic acid	Disulfide linkage in protein; transport of sulfur, its metabolite taurine: antioxidant; regulates cellular redox state; osmolyte, cellular metabolism and nutrition[32]	0.8	0.1
Histidine	(2*S*)-2-Amino-3-(1*H*-imidazol-5-yl) propanoic acid	Hemoproteins (*e.g.*, hemoglobin, myoglobin, catalase, and cytochrome c); production of CO (a signaling molecule); protein methylation; hemoglobin structure and function; antioxidative dipeptides; one-carbon unit metabolism; allergic reaction; vasodilator; central acetylcholine secretion; regulation of gut function; modulation of the immune response in skin[32]	2.4	2.8
Leucine	(2*S*)-2-Amino-4-methylpentanoic acid	Regulates protein turnover through cellular mTOR signaling and gene expression; activates glutamate dehydrogenase; branched-chain amino acids (BCAA) balance; helps regulate blood sugar levels, stimulates wound healing and produces growth hormones[32]	5.9	6.6
Lysine	(2*S*)-2,6-Diaminohexanoic acid	Major role in protein synthesis, hormone and enzyme production and calcium absorption. Important for energy production, immune function.[32] Regulates NO synthesis; antiviral activity (treatment of Herpes simplex); protein methylation (*e.g.*, trimethyllysine in calmodulin), acetylation, ubiquitination, and *O*-linked glycosylation[32]	5.5	5.7
Isoleucine	(2*S*,3*S*)-2-Amino-3-methylpentanoic acid	Involved in muscle metabolism; heavily concentrated in muscle tissue. Important for immune function, hemoglobin production and energy regulation[32]	4.0	4.5
Methionine	(2*S*)-2-Amino-4-methylsulfanylbutanoic acid	Important role in metabolism and detoxification. Necessary for tissue growth and Zn and Se absorption[32]	0.8	0.8
Phenylalanine	(2*S*)-2-Amino-3-phenylpropanoic acid	Activates tetrahydrobiopterin (BH_4) (a cofactor for NOS synthesis); tyrosine synthesis; neurological development and function. Precursor for neurotransmitters tyrosine, dopamine, epinephrine and norepinephrine[32]	4.8	4.8
Threonine	(2*S*,3*R*)-2-Amino-3-hydroxybutanoic acid	Principal part of structural proteins such as collagen and elastin, important components of skin and connective tissue. Plays a role in fat metabolism and immune function, synthesis of mucin protein required for maintaining intestinal integrity and function; immune function; protein phosphorylation and *O*-linked glycosylation; glycine synthesis[32]	3.0	3.1
Tryptophan	(2*S*)-2-Amino-3-(1*H*-indol-3-yl)propanoic acid	Neurotransmitter; inhibiting production of inflammatory cytokines and superoxide; inhibitor of BH4 synthesis; antioxidant; inhibition of the production of inflammatory cytokines and superoxide; antioxidant; inhibition of the production of inflammatory cytokines and superoxide; inhibiting the production of pro inflammatory T-helper-1 cytokines; preventing autoimmune neuro inflammation; enhancing immune function; a component of NAD and NADP, coenzymes for many oxidoreductases[32]	1.7	—
Tyrosine	(2*S*)-2-Amino-3-(4-hydroxyphenyl) propanoic acid	Protein phosphorylation, nitrosation, and sulfation. Its metabolites include (dopamine, epinephrine (EPN) and norepinephrine (NEPN), melanin) Neurotransmitter; regulates immune response, neurotransmitters; cell metabolism, antioxidant; inhibits the production of inflammatory cytokines and superoxide[32]	3.0	3.1
Valine	(2*S*)-2-Amino-3-methylbutanoic acid	Important for building and repairing muscle cells and involved in energy production; synthesis of glutamine and alanine; balance among BCAA[32]	4.4	4.9

coat[39,47] have phenolic acids with anti-inflammatory, anti-hyperglycemic and pro-apoptotic activities.[48] Marama seed coat extracts have potent anti-oxidant activity and protective effects against free radical induced erythrocyte haemolysis.[49] The polyphenol rich seed coat and cotyledons of marama bean interfere with the replicative pathways of rotavirus by reducing virus induced inflammation and the over-expression of nitric oxide.[50] Therefore, marama has major potential as an anti-microbial, anti-inflammatory, and anti-cancer agent (Table 4).

Table 3 Fatty acids in marama bean[22,39–41] '—' = not available

Fatty acid	Content (%)	IUPAC name	Chemical structure
Alpha-linolenic acid	—	(9*Z*,12*Z*,15*Z*)-Octadeca 9,12,15-trienoic acid	
Arachidic acid	3.00	Eicosanoic acid (or icosanoic acid)	
Arachidonic acid	0.368	(5*Z*,8*Z*,11*Z*,14*Z*)-Icosa-5,8,11,14-tetraenoic acid	
Behenic acid	1.28	Docosanoic acid	
Erucic acid	—	(*Z*)-Docos-13-enoic acid	
Linoleic acid	19–26	(9*Z*,12*Z*)-Octadeca-9,12-dienoic acid	
Myristic acid	—	Tetradecanoic acid	
Oleic acid	48–49	(9*Z*)-Octadec-9-enoic acid	
Palmitic acid	12–14	Hexadecanoic acid	
Palmitoleic acid	0.47	(9*Z*)-Hexadec-9-enoic acid	
Stearic acid	7–10	Octadecanoic acid	

5. Propagation of marama beans: towards attainment of food and nutrition security

The marama bean grows well in soil with low organic matter and low nutrient content, especially nitrogen. According to the Department of Agriculture, Forestry and Fisheries (South Africa),[16] marama bean prefers a neutral pH (7) soil and does not grow well under waterlogged conditions. The plant grows as a legume scrub, with long stems that can reach 3 m in length arising from a big underground tuber. It grows well in dry areas with less than 100 mm annual rain and with 250–600 mm optimum rainfall. It can be propagated through seed, in well prepared soil that is soft, well-drained and free of weeds. The seeds are planted (October–November) after being scarified to ensure proper germination.[16]

Scarification involves low temperature seed exposure to bring about prompt and uniform germination. Seed treatment is also important to prevent seed, soil and air borne diseases. Scarifying with boiling water or by soaking in water

Table 4 Phytochemicals in different parts of marama bean and their associated biological activities

Class of phytochemical	Compound	IUPAC	Plant part	Biological activity of compound in literature
Phenolic acids				
	Gallic acid	3,4,5-Trihydroxybenzoic acid	Cotyledon and seed coat[22, 39, 47]	Anti-carcinogenic, antimicrobial, anti-mutagenic, anti-angiogenic and anti-inflammatory agents[51]
	Protocatechuic acid	3,4-Dihydroxybenzoic acid	Seed coat, cotyledon and seed coat[39, 47]	Anti-inflammatory, anti-hyperglycemic, pro-apoptotic agent[48]
	p-Hydroxybenzoic acid	4-Hydroxybenzoic acid	Seed coat and cotyledon[39, 47]	Anti-oxidant[52]
	Vanillic acid	4-Hydroxy-3-methoxybenzoic acid	Seed coat and cotyledon[39, 47]	Anti-oxidant[53]
	Syringic acid	4 Hydroxy-3,5-dimethoxy-benzoic acid	Seed coat[39]	Anti-inflammatory activity[54]
	Caffeic acid	3,4-Dihydroxycinnamic acid	Seed coat and cotyledon[39, 47]	Anti-oxidant[55]
	p-Coumaric acid	(2*E*)-3-(4-Hydroxyphenyl)prop-2-enoic acid	Seed coat[39, 47]	Anti-microbial activity[56]
	Sinapic acid	3-(4-Hydroxy-3,5-dimethoxyphenyl)prop-2-enoic acid	Cotyledon, seed coat[39, 47]	Anti-oxidant, anti-inflammatory and anti-mutagenic agent[57, 58]
	Ferulic acid	(2*E*)-3-(4-Hydroxy-3-methoxyphenyl)prop-2-enoic acid	Cotyledon and seed coat[39, 47]	Anti-oxidant, anti-microbial activities[59]
	Tannic acid	[2,3-Dihydroxy-5-[[(2*R*,3*R*,4*S*,5*R*,6*S*)-3,4,5,6-tetrakis[[3,4-dihydroxy-5-(3,4,5-trihydroxybenzoyl)oxybenzoyl]oxy]oxan-2-yl]methoxycarbonyl]phenyl]3,4,5-trihydroxybenzoate	Seed[39]	Anti-oxidant[60]
Flavonoids				
	Fisetin	2-(3,4-Dihydroxyphenyl)-3,7-dihydroxychromen-4-one	Cotyledon and seed coat[39, 47]	Neurotrophic, anti-carcinogenic, anti-inflammatory, and other health beneficial effects[61]
	Myricetin	3,5,7-Trihydroxy-2-(3,4,5-trihydroxyphenyl)-4-chromenone	Seed coat[47]	Anti-oxidative and pro oxidative properties. It is a potent anti-carcinogen and anti-mutagen[62]
	Quercetin	2-(3,4-Dihydroxyphenyl)-3,5,7-trihydroxy-4*H*-chromen-4-one	Seed coat[39, 47]	Anti-oxidant, anti-inflammatory[63]
	Kaempferol	3,5,7-Trihydroxy-2-(4-hydroxyphenyl)-4*H*-1-benzopyran-4-one	Seed coat and cotyledon[39, 47]	Antioxidant, anti-inflammatory, anticancer[64]
	Astragalin	5,7-Dihydroxy-2-(4-hydroxyphenyl)-3-[(2*S*,3*R*,4*S*,5*S*,6*R*)-3,4,5-trihydroxy-6-(hydroxymethyl)oxan-2-yl]oxychromen-4-one	Seed coat, tuber[39]	Anti-oxidant, anti-bacterial activities[65]
	Rutin	2-(3,4-Dihydroxyphenyl)-5,7-dihydroxy-3-[(2*S*,3*R*,4*S*,5*S*,6*R*)-3,4,5-trihydroxy-6-[[(2*R*,3*R*,4*R*,5*R*,6*S*)-3,4,5-trihydroxy-6-methyloxan-2-yl]oxymethyl]oxan-2-yl]oxychromen-4-one	Seed coat, tuber and cotyledon[39, 47]	Antimicrobial, anti-inflammatory, anticancer, and antidiabetic[66]
	Naringin	(2*S*)-7-[(2*S*,3*R*,4*S*,5*S*,6*R*)-4,5-dihydroxy-6-(hydroxymethyl)-3-[(2*S*,3*R*,4*R*,5*R*,6*S*)-3,4,5-trihydroxy-6-methyloxan-2-yl]oxyoxan-2-yl]oxy-5-hydroxy-2-(4-hydroxyphenyl)-2,3-dihydrochromen-4-one	Tuber, cotyledon, seed coat[39, 47]	Anti-oxidant, antitumor, anti-inflammatory[67]
	Hesperidin	(2*S*)-5-Hydroxy-2-(3-hydroxy-4-methoxyphenyl)-7-[(2*S*,3*R*,4*S*,5*S*,6*R*)-3,4,5-trihydroxy-6-[[(2*R*,3*R*,4*R*,5*R*,6*S*)-3,4,5-trihydroxy-6-methyloxan-2-yl]oxymethyl]oxan-2-yl]oxy-2,3-dihydrochromen-4-one	Tuber, cotyledon, seed coat[39, 47]	Anti-inflammatory and analgesic[68]
	Catechin	(2*R*,3*S*)-2-(3,4-Dihydroxyphenyl)-3,4-dihydro-2*H*-chromene-3,5,7-triol	Cotyledon[39, 47]	Anti-oxidation and free-radical scavenging[69]
Benzofuranone	Griffonilide	(6*R*,7*S*,7a*S*)-6,7-Dihydroxy-7,7a-dihydro-6*H*-1-benzofuran 2-one	Tuber[50]	Anti-nociceptive, cytotoxic, antibacterial, antioxidant, and anti-amyloid properties[70]
Cyclohexene acetonitrile glycoside	Griffonin (Lithospermoside)	(2*Z*)-2-[(4*R*,5*S*,6*S*)-4,5-Dihydroxy-6-[(2*R*,3*R*,4*S*,5*S*,6*R*)-3,4,5-trihydroxy-6-(hydroxymethyl)oxan-2yl]oxycyclohex-2-en-1-ylidene]acetonitrile	Tuber[50]	Antimicrobial[50]
Phytosterols				
	Beta-sitosterol	(3*S*,8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-17-[(2*R*,5*R*)-5-Ethyl-6-methylheptan-2-yl]-10,13 dimethyl-2,3,4,7,8,9,11,12,14,15,16,17-dodecahydro-1*H*-cyclopenta[*a*]phenanthren-3-ol	Seed[39]	Anti-oxidant, anti-inflammatory[71]

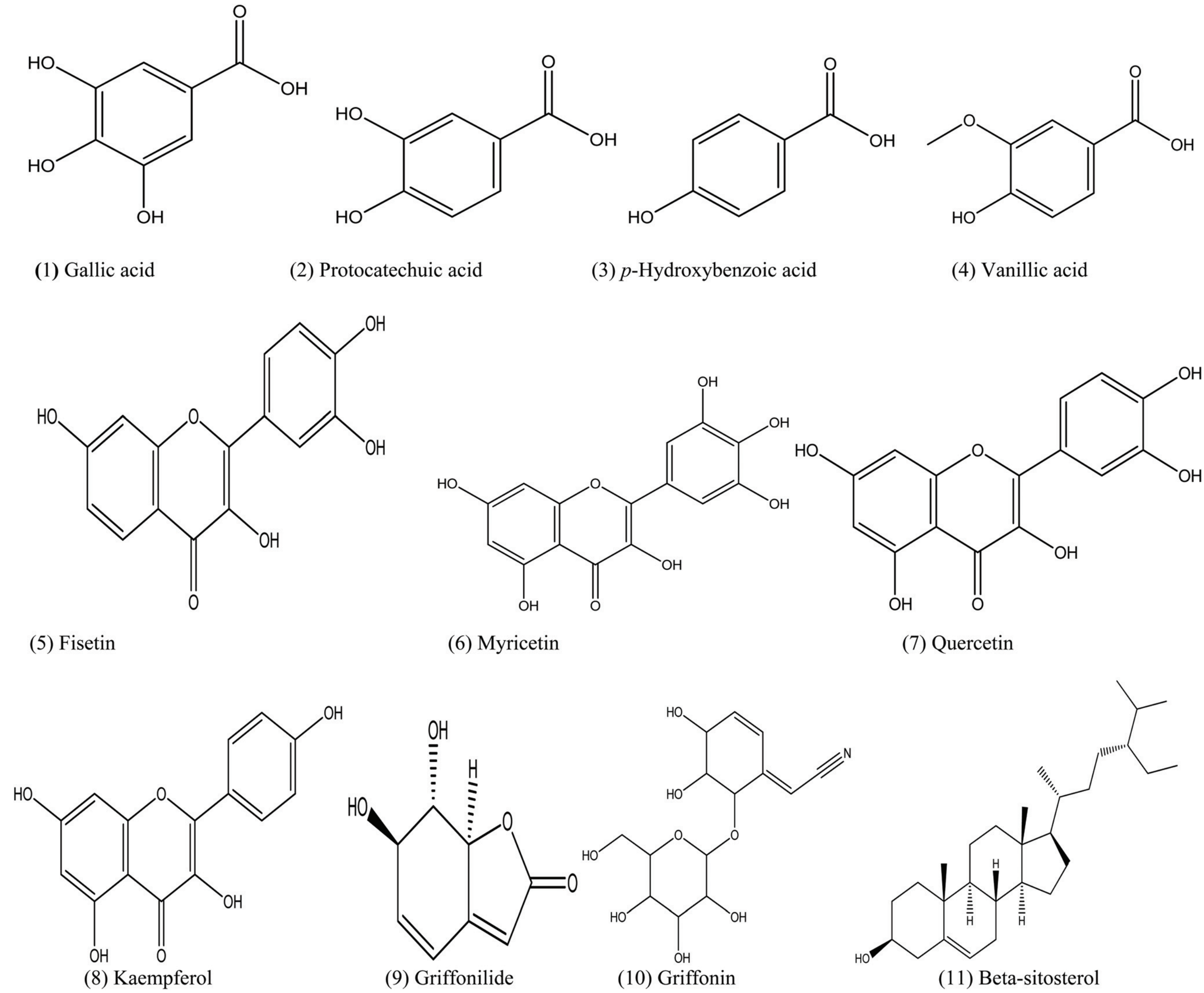


Fig. 3 Examples of the chemical structures of some selected phenolic acids, flavonoids and phytosterols in marama bean (*Tylosema esculentum*).

should be avoided as these methods kill the seeds.[39] For planting, the seeds are arranged in layers of sand in shallow boxes with pits and trenches to aid rapid germination, a method commonly used for peaches, cherries, oats and grapes.[72]

The plant needs 5–15 cm planting depth but 20 cm when the soils are wet, with one seed per hole being ideal.[16] Once germinated and growing, it does not need fertilizer or irrigation. However, it needs weeding, as well as pest and disease control from leaf eaters and pod borers which are the most problematic pests of marama beans and can be treated with standard sprays.[16] Harvesting and marketing (April–June) occurs when its pods are brownish in color, usually at the beginning of winter when the seeds are handpicked and the tubers are carefully dug and removed by hand to avoid scarring.[16]

6. Novel approaches for selection and improvement of marama bean

There is a need for conscious, efficient and directional improvement of the existing varieties of marama plants to increase the yield. Improvement of its quality, especially in micronutrients, should also be considered. Novel approaches such as next-generation sequencing and *de novo* domestication of marama bean may be pertinent.

6.1. Genetic diversity and next-generation sequencing of marama bean

As described by Takundwa *et al.*,[73] marama bean has a relatively small genome of about 1 Gb according to Feulgen staining. However, coverage of the genome in next-generation sequencing still requires confirmation by flow cytometry.[12] Although the chromosome number of marama bean is 42, there is no proper timing record of the genome duplications.[12] The genomic data were used to identify genes related to various important proteins including cysteine proteases and their inhibitors. It was also used to identify possible genes underlying self-incompatibility (heterostyly) by comparative analysis with the incompatibility genes from other plant species.[12,74]

Furthermore, genomic resources form the groundwork for developing genetic maps and useful DNA markers for marker-assisted selection (MAS) in marama bean.[75,76] Early studies have demonstrated a wide diversity among geographically distinct populations of marama bean.[7,77] This is to be expected for an outcrossing species that is self-incompatible and heterostylous. However, this may be difficult given the heterogeneity in plant varieties and the prevailing environmental situations of the source material available for breeding. Therefore, breeding of marama varieties is also likely to be difficult because the pollinators involved in fertilization and the production of plants and their range remain undefined.[12]

Better elucidation of the reproductive biology of marama beans is of scientific value and essential to accelerate breeding and improvement of the germplasm. The self-incompatibility of marama bean affects agronomic strategies. Compounding this characteristic, marama bean is a hexaploid (containing six homologous sets of chromosomes). Hence, employing molecular marker approaches will be a more complex strategy for identification of not only useful allelic polymorphisms, but also differences in duplicate loci.[78]

As reported by Takundwa *et al.*,[79] many polymorphisms were identified at the first screening with the aid of simple sequence repeats (SSRs) within a limited germplasm and clear polymorphisms within an individual. The SSRs data confirm earlier studies on wide variability within populations of marama bean. However, there may be specific attributes such as seed number per pod that has a more restricted distribution. There is a need to document the phenotypic as well as molecular diversity in order to select appropriate germplasm for an initial marama bean breeding population.

6.2. Application of *de novo* domestication for marama bean

Technological advancements in wild plant domestication have recently paved the way for *de novo* domestication of indigenous plants as a route for designing ideal crops for food and nutrition security.[80,81] *De novo* domestication is the introduction of domestication genes into non-domesticated plants; such re-domestication of wild relatives represents an important opportunity for fitting cultivated species to the climatic niche which they habit.[82] Given the current uncertainties due to climate change, increasing population, and deterioration of arable lands, it is important to consider the production of local food for human sustainability.[83]

Existing studies have established that in developing countries, about 10–15% of the land is cultivated by traditional methods while about 25 billion individuals cultivate food in smallholder farms for subsistence.[82] This indicates a large dependency on small scale farming methods which are unpredictable in terms of sustainable food supply. At the moment, *de novo* domestication application is still scanty but there are examples of how domestication genes were targeted in biotechnological methods that predate the development and widespread adoption of genome-editing techniques.[80] Two parallel approaches have been suggested for the *de novo* domestication of wild plants: traditional breeding approaches[84,85] and gene editing.[86]

For gene editing, the CRISPR/Cas9 approach is the method of choice in recent times.[86–88] This genome-editing tool, which is modified from a prokaryotic immune system, induces double-stranded DNA breaks by the action of Cas9 nuclease at a genome location corresponding to a designed guide RNA.[82,86] Intriguingly, studies[82,83,89] have suggested that restarting cultivation of lost plant species may be particularly valuable to the famers in developing nations since the local species are often already adapted to the local environment. Interestingly, marama bean[89] has been considered for genome sequencing by the African Orphan Crops Consortium (http://africanorphancrops.org/).

7. Challenges and possible ways to enhance the economic potential of marama beans

A number of challenges need to be addressed to foster the economics of marama bean; some of these are highlighted below:

7.1. Demand and supply dichotomy

Most developed countries use leguminous varieties in the production of different foods as increasingly health-conscious populations are looking for more nutritious foods.[90] In Africa, the quest for low cost but nutritious food (such as marama beans) is urgently needed, especially with increased expectation and demand for existing legumes. Breeding, domestication and commercial cultivation of marama bean could assist in closing the protein food supply gap as well as malnutrition. The lifestyle, tradition and culture of individuals can equally affect the demand and supply chain for the underutilized marama bean.

7.2. Affordability

Currently, legumes are some of the cheapest protein sources in the world.[91] In terms of the environment, indigenous legumes including marama beans are naturally less demanding to cultivate and are economical natural resources. Marama bean can be used in crop rotation, resulting in good yields for subsequent crops, which can in turn improve national food security. However, the affordability of marama bean may depend on the financial capability and economic status of individuals in any particular place.

7.3. Marama domestication, availability and accessibility

The breeding and domestication of marama bean must be encouraged in low and middle income nations, especially in countries where marama bean has comparative advantages over other legumes. Currently, marama is still mainly from the wild and research is needed on breeding (genome, genetic diversity and next-generation crop) to improve its yield. This will lead to increased availability and accessibility to potential consumers.

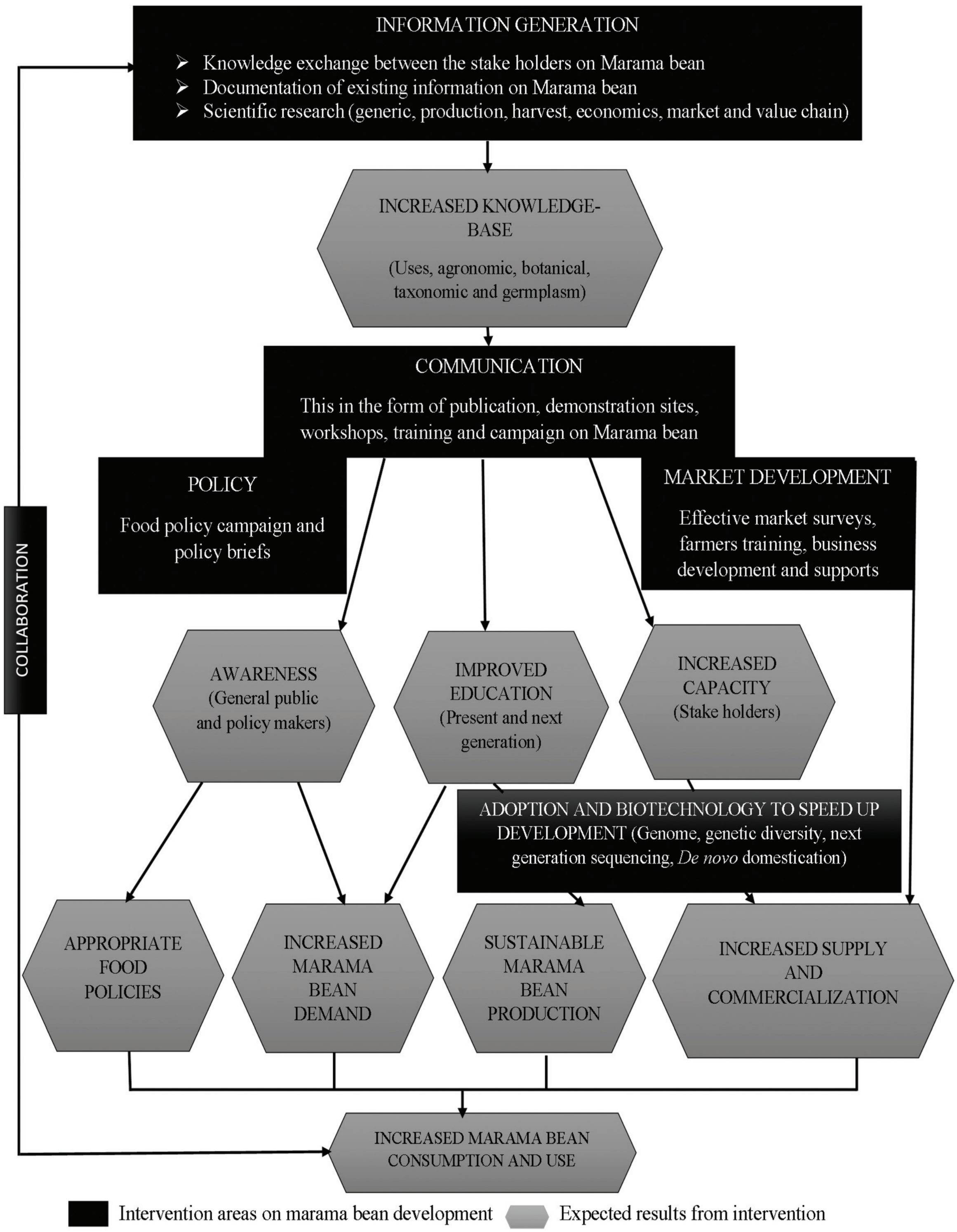


Fig. 4 Strategic framework of potential priority areas for policy and intervention on marama bean.

7.4. Awareness and education

Appropriate awareness and education about the benefits associated with marama will ultimately boost its productivity. This can be achieved by researchers, extension agents and other organizations through bulletins, newspapers, magazines, workshops, and training seminars. The cultivation of this plant can uplift rural areas and low-income groups. As most developed nations use legumes for food and because people are becoming increasingly health-conscious, proper awareness and education about marama bean are needed in developing nations for sustainability.[90]

7.5. Marketing opportunities and economic potential of marama bean and its products

Domestication and commercial cultivation of marama beans has the potential to address the shortage in protein food sources in Southern Africa. Increased plant production should be associated with distribution systems and markets for marama products. The expectations of producers, distributors and consumers of marama beans need to be established and strengthened. The South African region has a comparative advantage for producing this underutilized plant, and intensifying efforts in breeding, domesticating and producing more marama beans to alleviate food and nutrition insecurity would lead to significant economic prosperity. Developing countries could gain a competitive advantage by cultivating marama beans for local consumption and export markets. South Africa and other countries in the arid and semi-arid regions should put incentives in place to support local farmers and their markets and encourage the cultivation and marketing of marama beans.

8. Policy and intervention priority areas for the ideal marama bean

In response to the identified challenges associated with the economic potential of marama bean, multidisciplinary research and extensive collaboration among different stakeholders remain critical. As depicted in Fig. 4, a strategic framework that entails a wide range of stakeholders with coordinated efforts is essential to deal with many parts of marama development. Potential and priority areas for marama bean as an alternative protein rich food, as well as a source of nutrition security, were proposed through five (5) interventions in this review and are listed below.

(1) New knowledge generation through genetic mapping of marama bean and scientific research to expand the general knowledge.

(2) Effective transfer of generated data to raise awareness and build capacity amongst stakeholders. This can be facilitated through the use of demonstration sites, targeted campaigns, development of school curricula and training.

(3) Production of convincing evidence-based data that have the potential to influence policy at all levels and remove barriers to marama bean production and marketing.

(4) Improved market development through practical interventions, farmer training, and fostering public–private partnerships at all stages of the value chain to improve the supply and demand for marama and its products. These intervention areas are supported by improved interaction and partnerships amongst all stakeholders

(5) The use of biotechnology to speed up marama bean development through genomics and genome mapping activities, genetic diversity and next-generation sequencing.

In addition, the proposed framework highlights the links between these intervention areas and their expected effects. The following are the key effects:

(a) The worldwide knowledge base will be enhanced by scientific research, mapping the undervalued marama bean and documentation of existing information that are currently inaccessible.

(b) Through targeted communication in a variety of formats, this information will raise the awareness of the general public about the value of underutilized marama bean; relevant information will be fed into curriculum development to inform the present and next generation which will also contribute to capacity building amongst the primary stakeholders.

(c) Two main cases of 'communicating knowledge' have been highlighted. First, food policy has to remove existing barriers such as trade to arrive at appropriate policies with increased public awareness. Second, market development to improve the supply of quality marama bean.

(d) The prerequisites for continuing targeted research and development activities that will use and further increase the global knowledge base include increased capacity among primary stakeholders and a better educated younger generation. This will produce an iterative process that will enable sustainable growth in the production of and demand for marama bean and its products.

(e) Finally, when appropriate policies, increased demand, sustainable production and increased/better marama bean supply coincide, the goal of increased consumption/use of marama bean to address the overall development and food nutrition and economic sustainability problem will be reached.

9. Conclusion and recommendations

Presently, marama bean is mostly restricted to wild population which has resulted in high agronomic and nutritional variability. This review highlighted the nutritional, biological (anticarcinogenic, antimicrobial, anti-mutagenic, anti-angiogenic and anti-inflammatory properties) and phytochemical potential as well as the economic potential of marama bean. The plant has great potential to contribute to the livelihood of rural communities as well as resource-poor farmers, because the local environmental conditions are appropriate for its cultivation. The challenges confronting marama plant development were discussed with some novel approaches for selection and improvement of nutrition, health and economic sustainability. Particularly, there is a possibility of *de novo* domestication of marama bean as a viable solution for designing ideal crops while maintaining food security and a more sustainable low-input agriculture. In addition, there is a need for a multidisciplinary research approach that is aimed at efficient breeding and domestication for commercialization. Exploration of the value chain to enhance the commercial and economic value of marama bean is needed as well as the suggested interventions to improve the challenges associated with marama bean consumption. Overall, the review proposed priority areas for policy and intervention and recommends an all-inclusive and sustainable development approach as marama bean could support the attainment of the United Nations Sustainable Development Goals (UN SDG, 2030), in the areas of malnutrition, hunger eradication, economic prosperity and sustainability.

Author contributions

A. O. O. and A. O. A. conceptualized the project. A. O. O. sourced literature and prepared the manuscript with assistance from A. O. A.

Conflicts of interest

The authors of this work declare that there is no conflict of interest.

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