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***BALANITES AEGYPTIACA* (L.) DELILE IN THE SAHELIAN ARID ZONES: AN INTEGRATED SYNTHESIS OF ITS ECOLOGY, ETHNOBOTANY, PHYTOCHEMISTRY, PHARMACOLOGY AND SUSTAINABLE VALORIZATION POTENTIAL**

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ABSTRACT

Balanites aegyptiaca (L.) Delile (Zygophyllaceae) is an emblematic woody species of arid and semi-arid zones, characterized by remarkable ecological plasticity and strong multifunctionality. Present within Sahelian agro-sylvo-pastoral systems, it simultaneously contributes to food security, traditional medicine, rural economies, land restoration, and the provision of oilseed and energy products. This review aims to provide an integrated and critical synthesis of scientific knowledge on *B. aegyptiaca*, linking its taxonomy, geographic distribution, ecology, phenology, ethnobotanical uses, nutritional value, phytochemical profile, pharmacological properties, as well as its silvicultural and bioenergy potential. The literature search, conducted according to PRISMA principles, identified 78 scientific publications retained after screening for the final synthesis. Available data highlight substantial morphological, ecological and biochemical variability among populations and plant organs, as well as a richness in steroidal saponins, polyphenols, flavonoids, tocopherols and unsaturated fatty acids. Antioxidant, antidiabetic, anti-inflammatory, antimicrobial, antiparasitic and hepatoprotective activities are mainly documented by experimental studies, whereas nutritional, cosmetic and energy applications show significant valorization potential. However, translation of these findings into clinical applications and structured economic value chains remains limited. The development of multi-site research, domestication and genetic

conservation programs, together with toxicological and clinical validation, therefore constitute priorities for the sustainable valorization of the species in Sahelian arid territories.

Keywords: *Balanites aegyptiaca*; Sahel; Phytochemistry; Pharmacology; Silviculture; Biodiesel; Ethnobotany; Arid Zones

1 INTRODUCTION

Arid and semi-arid zones are characterized by high climatic variability, limited water availability and increased vulnerability to land degradation. In these environments, woody species play an essential role in ecosystem functioning and in providing food, fodder, medicinal and energy resources to rural populations [1]. The Sahel is therefore a priority area for strategies aimed at restoring and sustainably managing natural resources. In this context, the Great Green Wall (GGW), a pan-African initiative launched in 2007 under the auspices of the African Union, aims in particular to strengthen the restoration of degraded lands and the resilience of Sahelian territories [2]. The valorization of indigenous woody species adapted to local constraints is an important lever for these strategies. Among them, *Balanites aegyptiaca* (L.) Delile (Zygophyllaceae), commonly known as "desert date", occupies a particular position because of its wide distribution, its ability to persist in arid environments, and its long-standing integration into agro-sylvo-pastoral systems. Despite its importance, the species remains insufficiently integrated into structured programs for the management and valorization of forest resources [3]. Its use by local populations is ancient, as evidenced in particular by archaeological data dating back several millennia [4]. The multifunctionality of *B. aegyptiaca* is based on the diversity of uses associated with its different organs. Fruits, leaves, seeds, bark, roots and wood are exploited for food, medicinal, fodder, artisanal and energy purposes. This functional diversity is also associated with a complex biochemical composition including steroidal saponins, polyphenols, flavonoids, alkaloids, tocopherols, carotenoids and unsaturated fatty acids [5,4]. Several biological activities have thus been reported, including antioxidant, antidiabetic, anti-inflammatory, antimicrobial, antiparasitic, hepatoprotective and anticancer effects [5,6,4]. However, levels of evidence vary according to the activities, plant organs studied, preparations used and experimental models. In addition, the nutritional value of fruits and seeds, together with the properties of seed oil, gives the species valorization potential in the food, cosmetic and energy sectors. The oil has notably been investigated for biodiesel production, with encouraging results [7,8,9,10]. These different potentials strengthen the interest of *B. aegyptiaca* in strategies for the development and valorization of plant resources in arid zones. Despite the growing body of available work, knowledge of *B. aegyptiaca* remains dispersed across ecology, ethnobotany, nutrition, phytochemistry, pharmacology and forestry sciences. An integrative synthesis is therefore needed to link the biological and ecological characteristics of the species with its uses, properties and valorization opportunities.

This review therefore provides a critical and up-to-date synthesis of scientific knowledge on *B. aegyptiaca*, covering its taxonomy, geographic distribution, ecology, phenology, ethnobotanical uses, nutritional value, phytochemical composition, pharmacological properties, as well as its propagation, silviculture and bioenergy potential. It aims to identify the main achievements, valorization opportunities and research gaps in order to contribute to improved conservation, domestication and sustainable use of the species in African arid zones.

2 METHODOLOGY

This literature review was conducted according to the PRISMA 2020 principles to ensure the reproducibility and traceability of the search and publication-selection process [11]. The literature search was conducted in several scientific databases, including Web of Science, Scopus, PubMed/MEDLINE and Google Scholar, supplemented by several other databases. Searches focused on *Balanites aegyptiaca* and terms associated with its ecology, ethnobotany, phytochemistry, pharmacology, nutrition, propagation, silviculture and valorization. A total of 88 references were identified during the initial search (Figure 1). After removal of duplicates, unique references were screened on the basis of titles and abstracts, and potentially relevant publications were then assessed in full text. Inclusion criteria were mainly based on the relevance of the work to *B. aegyptiaca*, availability of usable scientific data and methodological quality of the studies. Duplicates, off-topic publications, documents not providing reliable data and publications not meeting the objectives of the review were excluded. At the end of the selection process, 78 publications were retained for the final synthesis.

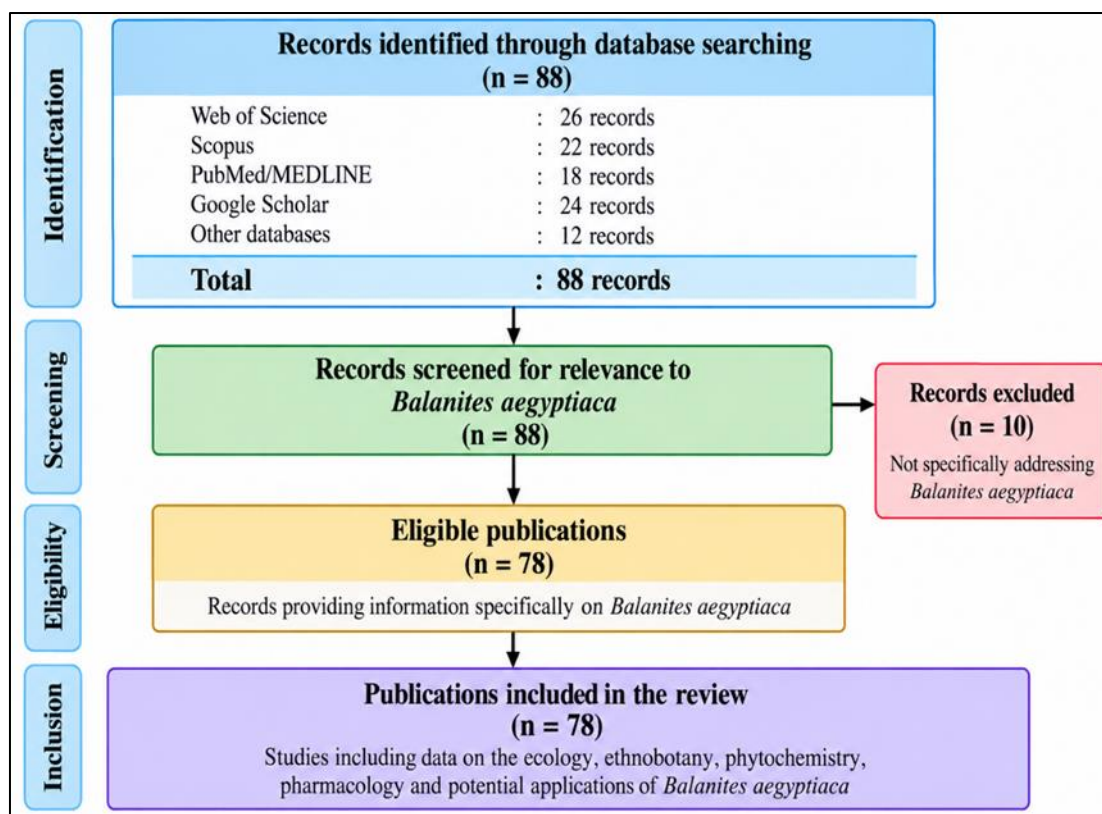


Figure 1: PRISMA flow diagram of the publication selection process.

The extracted information included botanical and ecological, ethnobotanical, phytochemical, pharmacological and silvicultural data. The data were then standardized and grouped into the main thematic areas presented in the Results section.

3 RESULTS

3.1 Taxonomy, nomenclature and botanical description

3.1.1 Systematic position and nomenclature

Balanites aegyptiaca (L.) Delile belongs to the family Zygophyllaceae R.Br., order Zygophyllales, within the Angiosperms, Eudicots and Rosids, in accordance with the APG IV phylogenetic classification [12]. The genus *Balanites* Delile, described by Delile in 1813, was taxonomically revised by Sands [13], who recognized nine species: *B. aegyptiaca*, *B. glabra*, *B. maughamii*, *B. orbicularis*, *B. pedicellaris*, *B. rotundifolia*, *B. roxburghii*, *B. welwitschii* and *B. wilsoniana* [5,4].

B. aegyptiaca comprises three varieties: var. *aegyptiaca*, var. *tomentosa* (Mildbr. & Schltr.) Sands and var. *quarrei* (De Wild.) G.C.C. Gilbert [13,4]. Several nomenclatural synonyms are also reported, including *Agialida aegyptiaca* (L.) Kuntze, *Agialida senegalensis* Van Tiegh., *Agialida tombouctensis* Van Tiegh., *Balanites ziziphoides* Mildbr. & Schltr. and *Ximenia aegyptiaca* L. [4]. Considering these synonyms is important to ensure comprehensive bibliographic searches and avoid omissions of older data relating to the species.

3.1.2 Vernacular nomenclature

Balanites aegyptiaca is known by numerous vernacular names according to regions and ethnolinguistic groups, reflecting its cultural and ethnobotanical importance throughout its distribution range. In Senegal, the species is known as Soump or Sump in Wolof, Goleteki or Muchitéki among the Fulani, and Séguéné in Bambara. In Nigeria, its Hausa name is Aduwa, while in Sudan and Egypt it is known by the Arabic names Heglig or Hijlij. It is called Mchunju in Swahili, Bedena in Amharic, Zachun in Hebrew and Tanni in Mali. In French, the most common names are Dattier du désert and Myrobolan d'Égypte [5,4,14].

3.1.3 Detailed morphological description

Balanites aegyptiaca is a thorny tree or shrub, evergreen to semi-deciduous depending on water conditions, reaching 6–10 m in height, with a trunk 30–60 cm in diameter; mature individuals may exceed 100 years of age [14,4] (see corresponding figure). The trunk, generally straight or slightly twisted, bears smooth green bark in young individuals, becoming brownish-gray and deeply longitudinally fissured with age. The branches bear robust, straight, green axillary spines 2–10 cm long, which contribute in particular to protection against herbivory [7]. Leaves are alternate and bifoliate, with two oblong to elliptic, leathery, glabrous to slightly pubescent leaflets, bright green on the upper surface and slightly glaucous on the lower surface; their structure shows xeromorphic characteristics, notably a thick cuticle and sunken stomata [3]. Flowers are small, greenish-yellow and hermaphroditic, grouped in axillary inflorescences, with five sepals, five petals, ten stamens and a superior ovary with five locules. Flowering is generally associated with rainy periods and may occur twice a year depending on the region [4]. In the Senegalese Ferlo, seasonal variation in visiting insects also highlights the role of the species in Sahelian pollination networks [6]. The fruit is an ellipsoid to ovoid drupe with a smooth surface, whose dimensions vary according to provenance. At maturity, the fleshy, dark-brown to yellowish-brown mesocarp surrounds a very hard woody endocarp containing an oil-bearing kernel. The mesocarp generally represents 25–40% of fruit weight, the endocarp 40–55% and the kernel 10–20%, with variation according to provenance [8,4]. The root system is particularly well developed and adapted to water constraints: it combines a taproot reaching approximately 2.90 m in depth with shallow lateral roots that can extend up to 22 m horizontally. The concentration of a large proportion of absorbing roots in the upper soil horizons allows efficient exploitation of low rainfall, while the differentiation of seven root types identified by Logbo et al. [15] indicates strong functional plasticity. Finally, the wood, hard and dense ($0.62\text{--}0.76\text{ g}\cdot\text{cm}^{-3}$), yellowish-brown and fine-grained, has an average gross calorific value of $19.26\text{ MJ}\cdot\text{kg}^{-1}$ at 13 years of age and produces good-quality charcoal with practically no smoke [14,16]. All these morphological and architectural characteristics give *B. aegyptiaca* a remarkable ability to persist in arid and semi-arid environments.

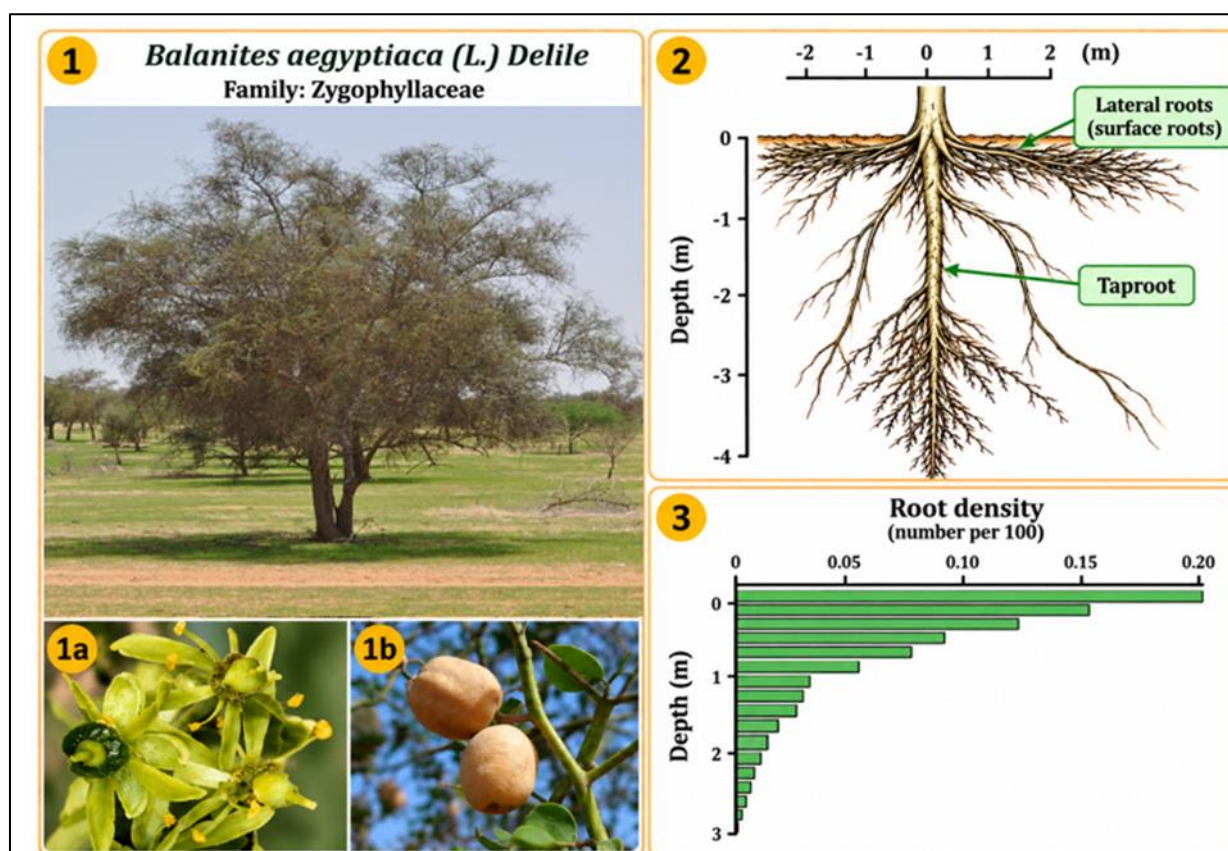


Figure 2: Morphology and architecture of the root system of *B. aegyptiaca* (L.) Delile: (1) general tree habit; (1a) flowers; (1b) fruits; (2) architecture and profile of absorbing roots; (3) density of absorbing roots according to soil depth.

3.1.4 Intraspecific morphological variability

Balanites aegyptiaca exhibits substantial morphological, biochemical and genetic variability among populations. In Egypt, Abdel-Farid and El-Sayed [17] identified, through metabolomics and multivariate analyses, three groups of individuals differing in their secondary-metabolite composition and antioxidant capacity.

In Senegal, studies by Sam et al. [18,19] reveal morphological and genetic diversity among Ferlo populations, consistent with local differentiation related to ecological conditions. Farmer criteria are based mainly on fruits (68.6% of citations), particularly taste (37.2%) and size (31.4%), followed by vegetative traits such as spines (15.7%), leaves (12.9%) and trunk (2.8%) [20]. This variability is also observed in Chad, where major differences in fruits and seeds have been reported among provenances from Ouaddaï [21], as well as in Ethiopia and Sudan, where genetic and morphophysiological diversity is associated with differentiated responses to water deficit [22].

Table 1: Comparative morphological variability of *B. aegyptiaca* populations in different regions

Region	Documented characteristics	Main observations	References
Senegal (Ferlo)	Variation in fruit size, pulp composition	Adaptation to Sahelian sandy environments	[23; 18;19]
Niger	Morphological variability among provenances	Ecotypic differentiation along climatic gradients	[24; 25; 26]
Chad (Ouaddaï)	Variation in seeds among provenances	Adaptive traits related to water deficit	[21]
Ethiopia/Sudan	Morphophysiological diversity	Differentiated adaptive responses to water stress	[22; 27]
Egypt	Variability in metabolomic profile	Three distinct groups according to metabolite contents	[17]
Mauritania	Variability in polyphenols and flavonoids	Higher concentrations in hyper-arid areas	[28]
Nigeria	Variability in yield and oil properties	Major geographic variations in oil quality	[29]

3.2 Geographic distribution and ecology

3.2.1 Distribution range

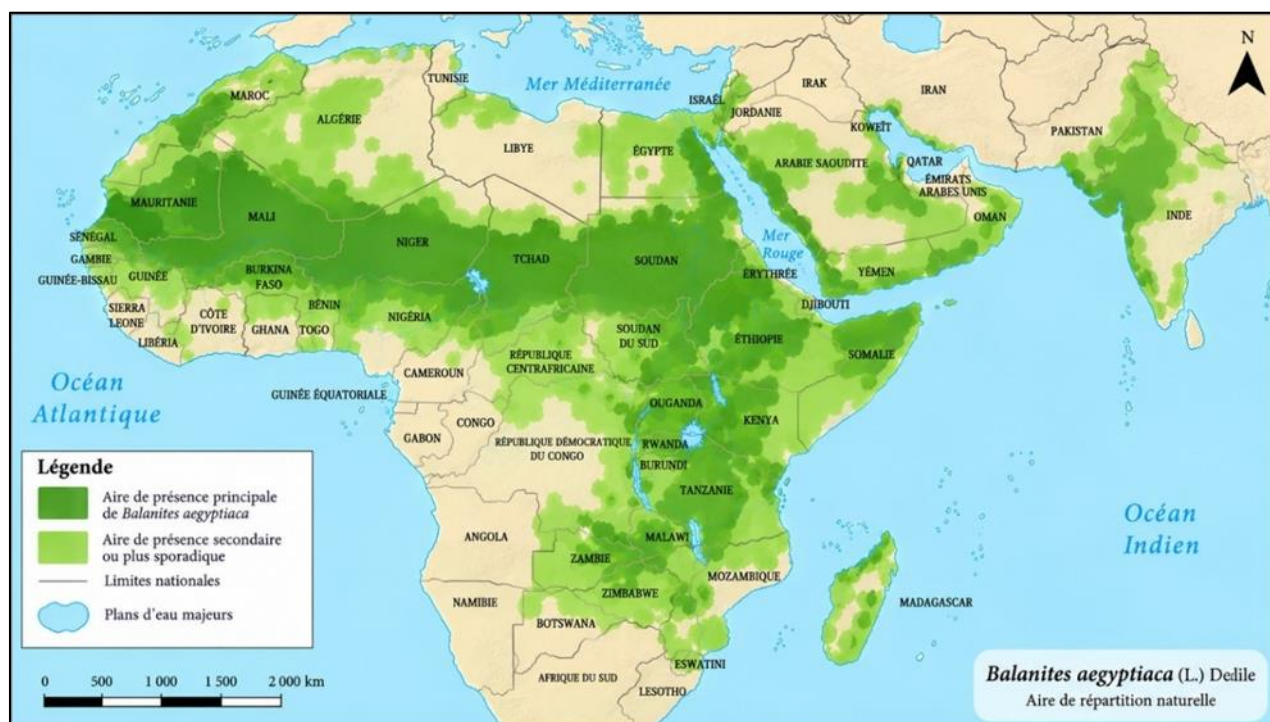


Figure 3: Natural geographic distribution of *B. aegyptiaca*. (Royal Botanic Gardens, Kew), PROTA and Orwa et al. (2009).

Balanites aegyptiaca is an Afro-Asian species with a wide geographic distribution, one of the largest ranges among Sahelian woody species. In Africa, it extends from the Atlantic, particularly Senegal and Mauritania, to the Red Sea and the Horn of Africa, and from the Sahara to Zimbabwe. The African range extends approximately between 16° W and 49° E and between 35° N and 19° S [14]. In Asia, the species occurs in the Middle East (Arabia, Jordan, Oman, Yemen), Iran,

India (Gujarat, Rajasthan, Madhya Pradesh), Pakistan and Myanmar [4,13]. The widespread variety *aegyptiaca* is characteristic of dry areas and extends into East Africa (Uganda, Kenya, Tanzania). Varieties *quarrei* and *tomentosa* are restricted to central-eastern Africa [20]. In Senegal, the species is abundant in the arid areas of Cayor and Ferlo and along the Senegal River, where it represents 36–79% of the woody vegetation depending on the site [30].

3.2.2 Ecological plasticity and adaptation to environmental variation

Balanites aegyptiaca has a broad ecological amplitude, developing under rainfall ranging from 100 to 1,300 mm/year, mean temperatures of 20–30 °C and at elevations of up to approximately 2,000 m. The species tolerates a wide diversity of soils and contrasting water conditions, ranging from temporary flooding to prolonged drought [31,32,14]. This plasticity allows it to occupy various Sahelian and Sudanian-Sahelian habitats and colonize degraded environments, giving it value for ecosystem restoration. However, its presence in some Sudanian areas may also be associated with situations of soil degradation [33]. Adaptation to water constraints is based notably on reduced leaf area, leathery leaves and the presence of spines, which help limit water loss and herbivory [34,4]. In the Ferlo, Fournier [35] showed that the species maintains high xylem tensions, with predawn water potentials of approximately –2.4 MPa in the dry season and –1.3 MPa in the rainy season, a turgor-loss osmotic potential of about –3.4 MPa and a maximum stomatal conductance of $0.26 \text{ mol m}^{-2} \text{ s}^{-1}$, indicating high tolerance to dehydration. Berger et al. [36] also demonstrated a distinctive water-use pattern characterized by high resistance to water transfer through the soil–root–plant continuum, which could be located at the roots and/or the soil–root interface [35]. Minimum hydraulic conductivity, estimated at approximately $1.6 \text{ mmol m}^{-2} \text{ s}^{-1} \text{ MPa}^{-1}$, is a component of the species' hydraulic functioning but is not by itself sufficient to demonstrate an adaptive mechanism [35]. Moreover, the ability to maintain high water tensions does not mean that the species can extract water indefinitely from extremely dry soils, because water availability decreases sharply when soil water potential becomes very low. Despite this ecological plasticity, modeling studies conducted in Chad, Ethiopia and Niger suggest potential vulnerability of *B. aegyptiaca* to climate change, with contraction of suitable habitat under some future climate scenarios [37,19,18]. These projections highlight the importance of habitat modeling in conservation and restoration strategies. In the Senegalese Ferlo, topography is also a determining factor in the distribution and structure of stands, particularly influencing their density and diameter structure [38].

3.3 Population ecology and stand dynamics

Balanites aegyptiaca is among the dominant woody species in many Sahelian stands, particularly in Senegal, Niger, Sudan and Chad [3,39,26,30,4]. This dominance is probably explained by its ability to persist in environments characterized by aridity and agropastoral disturbance, through functional traits that promote tolerance to water stress and grazing pressure. However, population demographic structure varies according to local ecological conditions, with half-bell-shaped, right-skewed or saw-tooth distributions reflecting differences in recruitment, growth and population renewal [38]. Grazing pressure is a limiting factor for regeneration, particularly in lowlands, where intensive grazing may reduce seedling and young-plant survival [26,30]. Conversely, protection from grazing improves vegetation productivity and promotes species regeneration [40]. Population distribution and structure are also strongly influenced by topography: in the Senegalese Sahel, lowlands and flats have the highest densities, with 78 and 62 individuals/ha, respectively, and also contain the largest individuals, whereas mounds and slopes support more sparse stands [30]. This spatial organization is particularly related to more favorable water availability in lower topographic positions. Soil and climatic conditions also influence morphological traits and fruit production, with fruits being heavier in the relatively humid areas of Ranérou than in the more arid sectors of Koyli Alpha and Labgar [18]. In addition, *B. aegyptiaca* contributes to biomass and carbon storage in Sahelian ecosystems. In Senegal, Ndiaye et al. [41] estimated mean aboveground biomass at $31.4 \pm 18.6 \text{ kg/tree}$ and carbon sequestration at $0.13\text{--}0.28 \text{ t C/ha}$, confirming the species' contribution to carbon storage and its potential value for land restoration and carbon-valorization mechanisms. The species also shows substantial intraspecific variation among provenances, particularly in growth, survival and wood density along Sahelian rainfall gradients [24,25]. Provenances from wetter areas generally show faster growth but lower tolerance to severe water stress, while geographic origin may also influence the chemical composition and biological activities of products from the species [27]. In Senegal, genetic analyses reveal significant differentiation among Ferlo populations, particularly in relation to limited gene flow between some sites [19]. Across the natural range, Chevallier et al. [42] estimated total genetic diversity at 81.5% and differentiation at 70.9%, with higher differentiation among northern Saharan populations (83.2%) than southern Saharan populations (63.5%).

3.4 Phenology

The phenology of *B. aegyptiaca* is characterized by strong persistence of phenological phases and substantial interannual and intersite variability, mainly under the influence of climatic and edaphic factors [43,30]. In the Senegalese Ferlo, the onset of leafing (Fe1) extends from May–June to September–October, with a maximum amplitude in August, whereas full leafing (Fe2) may persist almost throughout the year at some sites, giving the species a particularly evergreen character within the Sahel. Complete leaf fall (Fe0) is mainly observed at northern sites, notably Widou and Labgar, whereas it is almost absent at wetter southern sites such as Déali. In lowlands, foliage persistence is enhanced by greater soil-water availability [30]. Flowering is almost continuous throughout the year, but two main periods are distinguished

in the Ferlo: the first during the cool dry season, in November–December, and the second during the hot dry season, in March–April. It occurs earlier and over a longer period in lowlands than on flats [30]. Fruiting also has two main peaks, in November–December and May–June, but remains broadly spread over time because flowering and fruiting phases overlap. In some individuals, fruit maturation and fall may continue into the heart of the rainy season. Thus, Ndoeye et al. [43] and Sagna et al. [23] identify two main periods of fruit availability: the cool dry season (December–February) and the pre-rainy period (May–July).

3.5 Ethnobotanical and traditional uses

3.5.1 Local knowledge and food uses

Balanites aegyptiaca is a major food resource in Sahelian societies. In the Ferlo, 100% of the people surveyed by Sagna et al. [20] knew and used the species, whose different parts are valued for food purposes. The fruit pulp, with a sweet-bitter taste, is eaten fresh or dried and processed into beverages, flour, seasoning, nectar or fermented products [4]. Kernels provide edible oil, while young leaves and shoots are consumed as dry-season vegetables, particularly by the Iteso in Uganda [44]. Seeds are also eaten after cooking or roasting, and flowers are used as an infusion [45]. Across the Sahel, fruits and leaves also play an important fodder role during the dry season for cattle, sheep, goats and camels [46,44]. Wood has many domestic and artisanal uses, including construction, utensil making and fuel, and produces good-quality charcoal [47].

3.5.2 Medicinal uses of desert date

Balanites aegyptiaca occupies an important place in traditional Sahelian pharmacopoeias. All of its organs are used to treat various human and veterinary conditions, with uses reported notably in Senegal, Burkina Faso, Cameroon, Mauritania, Sudan, Mali and Nigeria [4,13]. Fruits are mainly used against gastric ulcers, hypertension, constipation, diabetes, jaundice, pain, rheumatism and hypercholesterolemia. Kernels are used as anthelmintics and against certain ocular, respiratory and digestive disorders. Bark, leaves and roots are involved in the traditional treatment of various hepatic, skin, respiratory and digestive disorders, as well as diseases such as epilepsy [4,13]. Uses vary considerably among regions. In Burkina Faso, fruits are notably associated with the management of hypertension [48]. In Cameroon, pulp, bark and twigs are used for digestive disorders, hypertension, skin conditions and oral hygiene [39]. In Mauritania, pulp is particularly used against diabetes, hypertension, cough and cardiovascular disorders, while seed oil also has therapeutic uses [28]. In Senegal, Sudan and Nigeria, numerous medicinal uses have also been documented [49,14,13]. The ethnomedicinal importance of the species is particularly pronounced in Mauritania, where more than 97% of respondents reported using the pulp against diabetes [28]. In Mali, *B. aegyptiaca* is also among the main plants traditionally used against hypertension [50]. Finally, the uses of the species extend beyond individual therapy: pulp and bark extracts have also been used to decontaminate water points in the fight against Guinea worm (*Dracunculus medinensis*).

Table 2: Traditional medicinal uses of *B. aegyptiaca* by region

Region	Parts used	Conditions treated	Preparation methods	References
Burkina Faso	Fruits	Arterial hypertension	Direct consumption	[48]
Cameroon	Pressed pulp, bark, twigs	Gastric ulcer, hypertension, constipation, burns	Decoction, maceration, calcination	[39]
Mauritania	Pulp, seed oil	Diabetes, hypertension, cough, skin infections	Infusion, topical application	[28]
Senegal	Fruits, leaves, spines	Mental disorders, various infections	Decoction, maceration	[20]
Uganda	Fruits, leaves	Functional food, malnutrition	Direct consumption	[44]
Sudan	Bark, fruits	Jaundice, liver diseases, helminthiasis	Decoction	[51]
Nigeria	Fruits, leaves, bark	Diabetes, intestinal worms, wounds, syphilis, dysentery	Decoction, maceration	[3]
Mali	Fruits, leaves	Arterial hypertension	Infusion, decoction	[50]
India	Fruits, seeds	Diabetic wounds (topical application)	Seed oil	[52; 53]

3.5.3 Cosmetic, industrial and veterinary uses

Oil extracted from the seeds is recognized for its remarkable cosmetic properties. Its richness in unsaturated fatty acids and tocopherols gives it emollient, nourishing and antioxidant properties that are particularly sought after in the cosmetic industry. Zang et al. [46] demonstrated its potential in the formulation of soaps and cosmetic lotions, while Manji et al. [54] highlighted the suitability of the oil as a raw material for producing biodegradable liquid cleansing agents. From a veterinary perspective, the species is used to treat helminth infections in domestic animals, particularly goats, in several West African countries [5,39]. Bark- and fruit-based preparations are also used to treat wounds and skin infections in livestock [3].

3.5.4 Economic and commercial uses

Fruit marketing is an important socioeconomic activity, involving mainly women and children. Fruits are sold in weekly local markets in the Ferlo at prices ranging from 150 to 200 FCFA per kilogram. Marketing data from the Linguère region of Senegal illustrate the growing commercial dynamics: officially declared quantities of products derived from *B. aegyptiaca* increased from approximately 20,725 metric tons in 2011 to more than 102,620 metric tons in 2012 [55]. The oil value chain involves a diverse network of economic actors: fruit collectors (31.25%), traders (29.17%), collector-traders (14.58%), artisanal processors (10.42%) and small and medium-sized enterprises (8.33%) [55].

3.6 Nutritional and phytochemical composition

3.6.1 Biochemical composition and food valorization of *B. aegyptiaca*

Table 3: Nutritional and phytochemical composition of different parts of *B. aegyptiaca*

Parameter	Fruit pulp	Leaves/Flowers	Whole seeds	Kernel	References
Crude protein (% DM)	5.4–9.6	16.9	25–35	29.5	[44; 23]
Lipids (% DM)	0.37–0.41	2.29	40–55	51.9	[44; 56]
Total carbohydrates (% DM)	42.6	ND	10–20	ND	[23]
Ash (% DM)	6.97	8.07	3–6	ND	[44]
Crude fiber (% DM)	ND	ND	5–10	ND	[57]
Potassium (mg/g)	19.54	19.54	ND	ND	[44]
Iron (µg/g)	452.21	452.21	ND	ND	[44]
Polyphenols (mg GAE/100 g DM)	264	ND	ND	ND	[28]
Total polyphenols (mg GAE/g extract)	ND	3.06	ND	ND	[45]
Total flavonoids (mg RE/g extract)	ND	21.60	ND	ND	[45]
Antioxidant activity	519 µmol TEAC/100 g DM	Present (IC ₅₀ = 1.07 mg/mL)	ND	ND	[28; 45]
Main flavonoids identified	ND	Rutin, quercitrin, hirsutrin, narcissin, ilixanthrin, isorhamnetin	ND	ND	[45]
Energy value (kcal/100 g DM)	212.25	ND	ND	ND	[23]

ND: Not determined in the sources consulted

The fruit pulp of *B. aegyptiaca* has substantial nutritional value. In the Senegalese Ferlo, it contains 42.57 g/100 g DM soluble sugars, 9.57 g/100 g DM proteins and 9.06 g/100 g DM ash, making it an interesting food resource for people and livestock, particularly during the food-gap periods [23]. It also contains 16 amino acids, including eight essential amino acids—leucine, valine, lysine, isoleucine, phenylalanine, threonine, histidine and methionine—with proline predominating at 1,172.5 mg/100 g DM [23]. In mineral terms, potassium is the major element (2,220 mg/100 g DM), followed by calcium, magnesium, sodium and phosphorus, while iron and zinc reach 4.94 and 0.65 mg/100 g DM,

respectively. This composition gives the pulp an energy value of 212.25 kcal/100 g DM and highlights its value as a complementary source of energy and micronutrients in Sahelian agro-sylvo-pastoral systems [23]. Leaves also have notable nutritional value, even exceeding that of pulp for some constituents: in Uganda, their crude protein content reaches 16.95%, compared with 5.4% in pulp [44]. In addition, pulp is an important source of bioactive compounds, with average contents in Mauritania of 264 mg GAE/100 g DM polyphenols and 34.2 mg QE/100 g DM flavonoids, associated with mean antioxidant activity of 519 μ mol TEAC/100 g DM, with higher activity in hyper-arid areas [28]. Flowers, which remain relatively poorly studied, also show food and functional valorization potential. They are traditionally consumed fresh or incorporated into various preparations, while Amadou et al. [45] developed an infusion of dried flowers, called Desert Date Tea (DDT), whose characteristics are comparable to those of some commercial plant-based beverages. This infusion is particularly rich in flavonoids (21.60 mg rutin equivalent/g extract) and phenolic compounds (3.06 mg gallic acid equivalent/g extract), while LC-MS analysis identified several compounds, including rutin, quercitrin, hirsutrin, narcissin, ilixanthrin and isorhamnetin. Its antioxidant activity and sensory acceptability, close to those of commercial green tea, reinforce the potential of *B. aegyptiaca* flowers for developing functional beverages and nutraceutical products [45].

3.6.2 Composition, properties and valorization of seed oil

Balanites aegyptiaca seed oil is an oilseed resource with high food, cosmetic and energy potential. Its content generally ranges from 41.5 to 52%, depending on provenance and extraction processes [40,7,55,8]. In Senegal, Sagna et al. [55] reported a mean content of $51.90 \pm 1.00\%$, while the seeds also have a protein content of approximately 29.5 g/100 g DM. The oil is characterized by a composition rich in unsaturated fatty acids, mainly linoleic and oleic acids, whose combined fraction reaches 69.16% in Senegal [55]. Its physicochemical properties, particularly saponification, iodine and acid values, vary according to provenance and extraction methods but remain generally compatible with different valorization pathways [40,7,10]. The presence of tocopherols, notably α -tocopherol (257 mg/kg) and γ -tocopherol (119 mg/kg), further strengthens its antioxidant and cosmetic interest [4]. El Harkaoui et al. [8] reported a mean sun protection factor of 11.5, while several studies highlight its potential in the food, cosmetic and industrial sectors [8,44]. Seed composition also strengthens its value for integrated valorization: seeds contain 25–35% protein, 40–55% lipids, 10–20% carbohydrates, 3–6% ash and 5–10% fiber [57]. After oil extraction, press cakes may contain 30–45% protein and a relatively balanced amino-acid profile, but their use as food requires prior treatment because of the presence of saponins, tannins, phytates, oxalates and protease inhibitors [57]. The oil is also of particular interest for biodiesel production, especially in arid and semi-arid regions where *B. aegyptiaca* can produce on marginal lands, thereby limiting direct competition with food crops [7,8].

Table 4: Main physicochemical properties of crude *B. aegyptiaca* oil

Property	Reported values	Source
Oil content	41.5–52 %	[10; 55]
Saponification value	172.5–216 mg KOH/g	[10;58]
Iodine value	7.42–78.5 g I ₂ /100 g	[59; 58]
Acid value	0.926–15.77 mg KOH/g	[10; 59]
Free fatty acids (FFA)	0.47–5.22 %	[10; 59]
Density	0.77–0.904 g/cm ³	[10; 59]
Kinematic viscosity	19.70 mm ² /s	[59]

The detailed physicochemical parameters of the crude oil are presented in the corresponding table. Transesterification, generally carried out with methanol and an alkaline catalyst such as KOH or NaOH, converts triglycerides into fatty acid methyl esters (FAME), with yields ranging from 82% to more than 98% depending on operating conditions [7,10]. When free fatty acid content is high, pretreatment may be required before transesterification [7,10].

The resulting biodiesel has characteristics broadly compatible with ASTM D6751 and EN 14214 standards for several parameters, including viscosity, flash point, density, iodine value and cetane number [40,7,10]. A cetane number of 54.02 has been reported [59]. Detailed values and their comparison with international standards are presented in the corresponding table.

Table 5: Comparison of *B. aegyptiaca* biodiesel properties with international standards

Property	<i>B. aegyptiaca</i> biodiesel	ASTM D6751	EN 14214	References
Kinematic viscosity at 40 °C (mm ² /s)	3.35–5.2	1.9–6.0	3.5–5.0	[10; 60; 58]
Flash point (°C)	112–170	>130	>120	[10; 58; 59; 60]
Cetane number	54.02	>47	>51	[59]
Density at 15 °C (kg/m ³)	718–904	875–900	860–900	[59; 60]
Iodine value (g I ₂ /100 g)	43.41–78.5	≤115	≤120	[58; 59; 60]

Finally, beyond its technical performance, the energy valorization of *B. aegyptiaca* has environmental relevance for Sahelian regions: Akaagerger et al. [10] reported a potential reduction of approximately 78% in CO₂ emissions compared with fossil diesel. Thus, *B. aegyptiaca* oil appears to be a multifunctional resource whose valorization could simultaneously contribute to the production of food and cosmetic products and to the development of renewable energy sources adapted to arid zones, provided that extraction and processing procedures are optimized and local value chains are structured [10,8,44].

3.7 Phytochemical profile

Balanites aegyptiaca has a diverse phytochemical profile dominated by steroidal saponins, polyphenols, flavonoids, coumarins, alkaloids, tocopherols, sterols and fatty acids, whose diversity underlies some of the biological activities attributed to the species [5,4]. Steroidal saponins, particularly balanitins 1–7, balanitoside, diosgenin and yamogenin, are characteristic compounds of the species; balanitins-6 and -7 notably exhibit cytotoxic and anticancer activities [5,61,62,63,4]. Polyphenols and flavonoids, such as quercetin, kaempferol and various phenolic acids, are mainly associated with antioxidant and anti-inflammatory activities [64,4]. Other metabolites, including coumarins (bergapten, D-marmesin), feruloyltyramine-type alkaloids, trigonelline, phytosterols, carotenoids, tannins and triterpenes, complete this chemical profile [32]. Seed oil is also distinguished by its richness in tocopherols, sterols and fatty acids, contributing to its nutritional and industrial properties [8]. Recent analytical approaches confirm this complexity: LC-MS/MS has identified matricin, isorhamnetin-3-O-rutinoside, rhoifolin and Assam saponin A in leaves [64], while metabolomic analyses combining GC-MS, LC-MS and NMR reveal strong qualitative and quantitative variability in metabolites among plant organs [26,30].

Table 6: Main secondary metabolites identified in *B. aegyptiaca* and their associated biological activities

Compound class	Main representatives	Plant parts	Biological activities	References
Steroidal saponins	Balanitins 1–7, balanitoside, diosgenin, yamogenin	Fruits, seeds, bark	Molluscicidal, antidiabetic, anticancer, hypocholesterolemic	[65; 4]
Polyphenols	Gallic acid, caffeic acid, chlorogenic acid	Fruits, leaves, galls	Antioxidant, anti-inflammatory, antimicrobial	[17; 4]
Flavonoids	Quercetin, kaempferol, rutin, luteolin	Fruits, leaves	Antioxidant, anti-inflammatory, anticancer	[65; 66]
Coumarins	Bergapten, marmesin	Leaves, bark	Antimicrobial, anticoagulant	[66]
Alkaloids	N-feruloyltyramines, trigonelline	Bark, roots, fruits	Antimicrobial, antifungal	[32]
Tocopherols	α-tocopherol (68.35%), γ-tocopherol (31.64%)	Seed oil	Antioxidant, photoprotective	[4; 55]
Sterols	β-sitosterol, stigmasterol, campesterol	Seeds, leaves	Hypocholesterolemic	[65]
Fatty acids	Linoleic, oleic, palmitic, stearic	Seed oil	Nutritional, emollient, biodiesel	[23; 56]

3.8 Pharmacological properties

Balanites aegyptiaca exhibits a broad spectrum of pharmacological activities, attributed in particular to its richness in polyphenols, flavonoids, tannins, saponins and other bioactive metabolites. Antioxidant, anti-inflammatory and analgesic activities have been reported, particularly with leaf and bark extracts [67,49]. Antidiabetic activities are among the best documented: hypoglycemic effects were observed as early as the work of El-Saadany et al. [68], while pilot clinical findings have also been reported in humans [69]. Leaf extracts can reduce blood glucose in diabetic rats [37], while the species may improve insulin secretion and limit pancreatic apoptosis through the SAPK/JNK pathway [5]. Hypocholesterolemic effects have also been described, notably in relation to steroidal saponins [70]. Regarding antimicrobial and antiparasitic activity, various extracts exhibit antibacterial and antifungal activities [49,51], while fruit extracts can inhibit aflatoxin production by *Aspergillus spp.* [71]. Antiparasitic activities include molluscicidal and anthelmintic effects [72,73,74]. Anticancer and immunomodulatory properties are mainly documented by in vitro and preclinical studies: balanitins-6 and -7 exhibit antitumor activity [63], and antiangiogenic and antitumor effects have also been reported for bark [75]. Immunomodulatory activities have also been described [76], while nanoparticles combining *B. aegyptiaca* and chitosan have shown effects on experimental liver fibrosis [77]. The species also has hepatoprotective properties, demonstrated with leaf extracts in rats [78] and with an aqueous root-bark extract in Burkina Faso [79]. Other activities have been reported, including wound-healing, diuretic, nephroprotective, neuroprotective and cardioprotective effects [52,34,80,81,31]. Despite this pharmacological potential, the presence of antinutritional factors such as saponins, tannins, oxalates and phytates must be considered when assessing safety of use [57,82]. Toxicological studies also report variable effects depending on organisms, extracts and doses studied [83,84]. These observations highlight the need for continued toxicological investigations to define doses, forms of use and conditions ensuring safe use of *B. aegyptiaca*.

Table 7: Summary of the main pharmacological activities of *B. aegyptiaca*

Activity	Plant organ	Extract type	Model	Active compounds	Key results	Limitations	References
Antioxidant	Fruits, leaves	Methanolic, aqueous extracts	In vitro tests (DPPH, FRAP, ABTS)	Polyphenols, flavonoids, tannins	Strong free-radical scavenging activity	Protocol variability	[28; 49]
Anti-inflammatory	Fruits, bark, root	Crude extracts	Rat models	Steroidal saponins, phenolic compounds	Significant reduction in edema	Few mechanistic studies	[67; 85]
Antidiabetic	Fruits, leaves, seeds	Aqueous and organic extracts	Diabetic rats, pilot clinical trial	Saponins, diosgenin glycosides	Significant decrease in blood glucose	Few clinical trials	[68; 69]
Hypocholesterolemic	Fruit pulp	Aqueous extracts	Animal models	Saponins	Reduction in total cholesterol and LDL	Older studies requiring confirmation	[70]
Antimicrobial	Fruits, bark, leaves, oil	Methanolic, chloroform, aqueous extracts	In vitro tests	Polyphenols, saponins, alkaloids	Inhibition zones 23–25 mm (<i>E. coli</i> , <i>K. pneumoniae</i>)	Inconsistent results among studies	[51; 81]
Antiparasitic	Fruits, roots	Aqueous and saponin extracts	In vitro and in vivo	Balanitins, deltonin	Molluscicidal, anthelmintic, antimalarial	Need for comprehensive in vivo studies	[72; 73; 74]
Anticancer	Fruits, stem bark	Organic extracts, purified fractions	Cell lines, mouse models	Balanitin-6, balanitin-7, balanitoside	Induction of apoptosis, inhibition of proliferation	Absence of clinical trials	[63; 75]

Hepato protecti ve	Bark, fruits	Plant extracts	Animal models	Polyphenols, flavonoids	Protection against oxidative liver damage	Few toxicological studies	[84; 79]
Wound healing	Seed oil	Fixed oil	Clinical case studies	Unsaturated fatty acids, tocopherols	Accelerated healing of diabetic wounds	Insufficient clinical validation	[52; 53]

3.9 Nutritional value and use in animal feeding

Balanites aegyptiaca has potential as an alternative feed resource in livestock production. Its seeds, oil and press cakes have been studied in ruminants, poultry, fish and rabbits, with favorable effects reported on some zootechnical parameters, notably growth, survival and certain physiological indicators [44]. However, use of seeds and press cakes is limited by the presence of antinutritional factors, particularly saponins, tannins and phytates. Treatments such as cooking, fermentation, roasting and ethanol extraction can reduce their levels and improve the nutritional valorization of these products [57]. Thus, *B. aegyptiaca* represents a potential resource for diversifying animal feed in Sahelian areas, provided that seeds and press cakes are appropriately treated to limit the effects of antinutritional compounds [5,57].

3.10 Silviculture, propagation and fruit production

Regeneration of *B. aegyptiaca* is mainly limited by seed-coat dormancy associated with the hardness and impermeability of the endocarp. Scarification, prolonged soaking and certain chemical treatments substantially improve germination, with rates reaching 70–90% depending on provenance and protocol [13,32]. Germination performance nevertheless varies among provenances, highlighting the importance of selecting appropriate plant material [24,25]. Natural regeneration can also be promoted by zoochory, with seeds recovered from livestock feces showing germination rates of 47–71% and field establishment rates of 90–100% [86]. In plantations, protection of young plants against herbivory remains necessary during the first years [3].

Vegetative propagation is an alternative to sexual propagation, particularly for conserving and disseminating genotypes with desirable traits. Air layering provides a mean survival rate of 68.5%, reaching 83.1% for branches 2–3 cm in diameter [87]. Cutting, layering and grafting have also proven feasible under Sahelian conditions [9]. From a biotechnological perspective, micropropagation from axillary buds of adult trees on MS medium supplemented with BAP and then IBA for rooting resulted in 48% survival after acclimatization [43,9]. In plantations, *B. aegyptiaca* grows relatively slowly, but this characteristic is associated with long lifespan and high resilience in harsh environments. Growth performance varies according to rainfall gradients and provenances, reflecting adaptation to local climatic conditions [24,25], while in the Senegalese Ferlo, radial growth is sensitive to interannual climatic variation [62].

Fruit production varies greatly among individuals, sites and ecological conditions. Under favorable conditions, production can reach 100–150 kg of fruit per mature tree [65]. In Burkina Faso, large trees with well-developed crowns are generally the most productive, while individuals retained in agricultural and agroforestry systems may have higher production than natural stands subject to high grazing pressure [88]. In the Senegalese Great Green Wall zone, Sagna et al. [61] recorded mean yields ranging from 0.6 to 14.8 kg tree⁻¹ and productivities of 21.1 to 547.5 kg ha⁻¹ depending on site. This variability is mainly related to stand demographic structure, tree size and maturity, and local edaphic and hydrological conditions, which determine the expression of fruit-production potential [61].

4 INTEGRATION INTO CONSERVATION AND REFORESTATION POLICIES

Balanites aegyptiaca is a woody species of major interest for the restoration of Sahelian ecosystems, particularly within the framework of the Great Green Wall (GGW). In Senegal, it is associated with other indigenous species adapted to aridity, such as *Senegalia senegal*, *Vachellia tortilis* subsp. *raddiana*, *Sclerocarya birrea* and *Ziziphus mauritiana*. Its value is based on the convergence of several ecological, food, medicinal and socioeconomic functions [43,14,13].

In the Ferlo, studies by Sagna et al. [4,38,13,8,55] constitute an important body of data on the ecology, valorization and potential of the species. *Balanites aegyptiaca* is also integrated into agroforestry systems and Sahelian parklands, where its multifunctionality simultaneously contributes to livelihoods and ecosystem functioning. The species provides food, medicinal, fodder and energy resources, while also contributing to local environmental regulation through shading, reduction of wind erosion, improved water infiltration and nutrient cycling [3]. Thus, the value of *B. aegyptiaca* for the GGW lies not only in its tolerance of arid conditions, but also in its ability to combine ecological restoration, resource production and ecosystem services, making it a particularly relevant component of multifunctional Sahelian restoration systems [43,14,13].

5 CONCLUSION

This synthesis shows that *B. aegyptiaca* is a major multifunctional species of African arid and semi-arid zones, at the interface of ecological restoration, food security, health, rural development and energy-transition challenges. Its strong capacity to adapt to water and edaphic constraints, combined with its nutritional value, phytochemical richness, ethnobotanical uses and multiple valorization opportunities, gives it particular importance in Sahelian sustainable-development strategies.

However, a gap persists between the ecological and socioeconomic importance of the species and the level of knowledge required for its domestication and large-scale valorization. The main gaps concern genetic structure across the distribution range, identification of high-performing genotypes, optimization of silvicultural practices, understanding of adaptation mechanisms to environmental stresses and climate change, as well as pharmacological, toxicological and clinical validation of certain medicinal uses.

The economic potential of the species also remains largely underexploited. Fruits, seeds, oils, leaves, flowers and by-products offer valorization opportunities in the food, fodder, cosmetic, pharmaceutical and energy sectors. Development of structured value chains could therefore contribute to income diversification and strengthen the resilience of rural communities.

In the context of the Great Green Wall, *B. aegyptiaca* is a particularly relevant model for combining ecological restoration, biodiversity conservation and territorial development. Its ability to persist in harsh environments and simultaneously provide food, medicinal, economic and energy products strengthens its relevance to strategies for adapting to and restoring degraded lands.

Recommendations

In view of the gaps identified, several research and action priorities can be retained:

- characterize the genetic diversity of the species across its distribution range in order to identify provenances and genotypes with traits of interest for domestication, restoration and adaptation to local conditions, particularly through population-genomics approaches;
- establish standardized multi-site trials covering the main climatic gradients to assess growth, fruit productivity, biomass and carbon sequestration;
- strengthen phytochemical, pharmacological and toxicological research by integrating metabolomic and pharmacokinetic approaches and controlled clinical trials, particularly for antidiabetic and anti-inflammatory activities;
- develop standardized studies on digestibility and the nutritional value of seeds, oils and press cakes in different animal species;
- deepen evaluation of the bioenergy potential of the oil by integrating techno-economic and environmental analyses of biodiesel value chains adapted to Sahelian contexts;
- develop research on value chains, product profitability and market access, while promoting participatory approaches involving researchers, local communities, technical services, decision-makers and the private sector.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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The authors declare that they have no financial, professional or personal conflicts of interest that could have influenced the conduct, analysis or writing of this work.

Author contributions

- **Moustapha Bassimbe Sagna:** conceptualization, methodology, bibliographic research, data organization, data analysis and interpretation, manuscript writing and coordination of the work.
- **Alimatou Sam:** data collection and organization, analysis and manuscript revision.
- **Khoudia Niang:** data collection and organization, analysis and manuscript revision.

- **Aly Diallo:** manuscript revision.
- **Aliou Guisse:** scientific supervision and critical manuscript revision.
- **Gilles Boetsch:** bibliographic research, scientific supervision and critical manuscript revision.

Data availability

The synthesized data come from the scientific literature cited in the manuscript.

Use of artificial intelligence

The authors declare that artificial intelligence (AI) tools were used solely for translating the manuscript initially written in French into English and for improving the linguistic quality of the text. AI was used in particular to improve clarity, grammar, syntax and writing style.

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