Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-11

DOI: *10.15244/pjoes/217449* ONLINE PUBLICATION DATE: 2026-05-06

Review

Micropropagation of Gum Arabic Tree (*Acacia senegal*): An Economically and Ecologically Important Sub-Saharan African Tree

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Received: 20 November 2025
Accepted: 27 January 2026

Abstract

Gum arabic (*Acacia senegal*) is a multipurpose tree widely distributed throughout the Sudano-Sahelian region of sub-Saharan Africa, extending from Sudan to Senegal. It is best known for being the main source of high-quality commercial gum arabic, a bark exudate used in a variety of food, pharmaceutical, and industrial products. Gum arabic trees are conventionally propagated through seeds. However, in addition to the difficulty in obtaining selected seeds every year, poor germination, and the death of young seedlings in the natural habitat, this method results in high genetic diversity within the species' populations. *In vitro* micropropagation may be the best substitute to avoid the drawbacks of traditional propagation. Micropropagation promotes large-scale commercial plantations and sustainable agriculture to satisfy the growing global demand for gum arabic. Additionally, it can be used for conservation, genetic enhancement, and production of disease-free planting materials. However, despite its potential, gum arabic tree micropropagation methods face several difficulties, including a poor multiplication rate, low rooting, and a high mortality rate during acclimatization. In this review, we first provide an overview of gum arabic trees and their conventional means of propagation, and then describe all published research and the most up-to-date information on the progress made in the field of gum arabic tree micropropagation from 1973 to 2025. The challenges and future perspectives of this study are also outlined.

Keywords: gum arabic, *Acacia senegal*, micropropagation, organogenesis, somatic embryogenesis

Introduction

The gum arabic tree (*Acacia senegal*) is a multipurpose leguminous tree that is extensively distributed throughout the arid and semi-arid parts of sub-Saharan Africa [1]. It is best known as the main source of high-quality commercial gum arabic, which is a versatile stabilizer and thickener used in different items, including food, beverages, pharmaceuticals, and industrial products like inks and adhesives. The gum arabic tree is economically important for producing areas, which are mainly sub-Saharan African countries, as it provides

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a considerable source of foreign exchange and revenues [2-4].

Ecologically, gum arabic trees are an important species in their natural habitat because they improve soil fertility by using active root nodules to fix nitrogen from the atmosphere [4]. Additionally, they are admirably adapted to arid conditions and help prevent soil erosion, provide a natural habitat for local wildlife, combat desertification, and are useful for afforestation programs [5].

Despite their economic and ecological importance, gum arabic trees remain underexploited in terms of their genetic improvement and breeding. Conventionally, they are propagated through seeds; however, difficulties in collecting seeds each year, storing seeds, poor germination, and the death of young seedlings due to extreme aridity often do not allow for a sufficient supply of seedlings for reforestation [6, 7]. Moreover, propagation through seeds allows for substantial genetic variation within populations, and gum arabic trees in particular demonstrate great intraspecific diversity, with yearly yields ranging from 0 to 1 kg per tree [8, 9]. Therefore, propagation via seeds is not an appropriate method for producing true-to-type plants [6]. In contrast, micropropagation offers a powerful alternative for large-scale year-round production of genetically uniform and elite planting materials [10]. Micropropagation tools, along with traditional tree improvement techniques, hold promise for accelerating breeding programs, supplying disease-free seedlings, and conserving endangered gum arabic trees [11]. However, micropropagation protocols for gum arabic trees are few, fragmented, and poorly optimized. Most existing studies have focused only on direct or indirect organogenesis with limited success in shoot regeneration, rooting, and full plantlet acclimatization.

This review aims to address the gaps in the micropropagation of *Acacia senegal* by highlighting research findings and challenges from 1973 to 2025, thus helping the scientific community advance future research constructively. Overall, overcoming these challenges will help ensure the successful large-scale propagation of this economically and ecologically important sub-Saharan African tree using micropropagation techniques, which will boost reforestation operations and conservation programs. Table 1 summarizes all micropropagation research on *A. senegal*. Fig. 1 depicts a general system for *A. senegal in vitro* micropropagation methods.

Geographic Distribution

Gum arabic trees are widely distributed in tropical and subtropical regions across Africa, from the Sahelian Belt to southern Africa [12]. They are grown in sub-Saharan African countries, such as Mali, Senegal, and Mauritania in the western part; Niger, Benin, Nigeria, Burkina Faso, Cameroon, and Chad in the north-central area; Sudan, Somalia, Eritrea, and Ethiopia in the east; and Angola, Mozambique, Botswana, Zimbabwe, Namibia, and South Africa in the south. In addition to Africa, *A. senegal* grows in India, Pakistan, and Oman [2]. Gum arabic trees grow on poorly drained soils, such as clay sandstones, brown clay, or sandy clay, in regions with an average annual precipitation of up to 800 mm [2]. Generally, well-drained sandy soils with an annual rainfall of 200-500 mm and a mild sub-desert climate are ideal for gum arabic tree growth [13].

Botanical Overview

The genus *Acacia* belongs to the Mimosoideae subfamily of the third-largest family, Fabaceae (pea family). It is a deciduous shrub that reaches 2-12 m above the ground [14]. The trunk is covered with strong, hooked thorns that are 3-5 mm long. Leaves are bipinnate, with two sharply recurved stipulate spines and a third pseudo-stipular spine in between; the rachis is up to 2.5 cm long; pinnacles are in pairs of 8-15 green; and 3-8 pinnae [15]. Flowers are fragrant and yellowish-white, with axillary pedunculate spikes that are cylindrical and 5-10 cm long. Each flower's calyx has 5 deep lobes, 5 petals, and a multitude of short stamens. The pods are rectangular, straight, thin, flat, and short-stipitate. They are green and pubescent when young and turn shiny bronze as they mature. The seeds are smooth, flat, small, shiny, and dark brown [16].

Ecological Characteristics

Gum arabic trees are drought-tolerant and naturally grow in arid, subtropical, and semi-arid climatic areas [17]. They can grow on several types of soil with varied levels of pH and temperatures [18]. They are widely known for having a strong resistance to water stress [19]. They can tolerate high daily temperatures (45ºC), arid winds, and sandstorms. They prefer coarse-textured and well-drained soils such as fossil dunes, but it grows on slightly loamy sands, skeletal soils such as lithosol, and heavy clay soils with 800 mm annual rainfall. Gum arabic trees are very crucial to the environment since they increase soil fertility and are frequently employed to combat desertification [20]. Therefore, they might be appropriate for restoration and reforestation in arid and semi-arid regions with little rainfall [21]. *A. senegal* is commonly associated with various kinds of natural habitats, including Anogeissus forests and semi-desert grazing fields. It favors rocky hill slopes and clay plains. In Sudan, the gum arabic tree can be found as a wild tree, mostly grown on sandy hills or cultivated on clay soil [17].

Economic Importance and Medicinal Uses

Gum arabic is a natural forest substance extracted from the stems and branches of different *Acacia* species [22]. However, *A. senegal* is the main source of high-quality commercial gum arabic that is used worldwide

[2]. Owing to its versatility and safety record, gum arabic is utilized in the manufacture of paper, textiles, ink, glue, paint, printing, food, medicine, and cosmetics [23], and it is considered an essential component of Sahelian countries' economy; a sizable amount of the crude gum produced in these countries is exported to the US, UK, France, Germany, and India [22]. In 1992-94, the average yearly gum exports, including raw and semi-processed gum, were approximately 35,000 tons. In 2014-16, this amount increased to 102,000 tons. The exports of processed gum rose from 17,000 tons to 53,000 tons. Semi-processed and raw gum contributed 56% and 44%, respectively, to the average annual value of gum arabic exports in 2014-16, which was $337 million [2].

Gum arabic has been used for centuries in traditional medicine to treat a wide range of diseases, including typhoid, gonorrhea, diarrhea, cough, sore throat, intestinal inflammation, and urinary tract infections [24]. It is also used externally to treat irritating areas, such as nodular leprosy, burns, wounds, and irritable nipples [25]. Gum arabic's antioxidant qualities, possible effects on lipid metabolism and renal function, and capacity to neutralize reactive oxygen species have already been demonstrated [26]. Gum arabic has demonstrated the ability to alleviate the consequences of chronic renal failure by enhancing creatinine clearance and calcium and magnesium production [27]. Additionally, it has been shown that gum arabic drastically reduces caloric intake and lowers blood pressure in rats, possibly because increased dietary fiber intake promotes satiety [28]. Gum arabic is a good candidate for supplemental weight control treatments because of the decrease in energy intake. It has been shown to have antimicrobial activity against several human pathogenic bacteria and fungi [29]. Moreover, gum arabic is frequently employed as a drug trial vehicle in pharmacological and physiological studies [30].

Results

Conventional Propagation of Gum Arabic Tree

Conventionally, the gum arabic tree is propagated through either sexual (seeds) or asexual/vegetative (cuttings and other plant parts) means.

Seed Propagation

For gum arabic trees, sexual propagation through seeds remains the simplest and most natural means of producing new plants. However, several factors can impede this process, such as the difficulty of acquiring selected seeds every year, difficulties in storing seeds, inadequate germination, and the death of young plants in their native environment, which do not consistently allow sufficient production of selected seedlings for reforestation [6]. Additionally, the tough outer coat of *Acacia* seeds is water-impermeable, which hinders seed germination. Therefore, before utilization in afforestation, reforestation, or other forms of ecological restoration, *Acacia* seeds frequently need to undergo pretreatment in the laboratory to make them water-permeable [31]. Pretreatment techniques increase the chance of successful seedling growth by breaking down the seed coat and promoting germination. Among these methods, soaking in water is a straightforward, popular, and successful way to pretreat *Acacia* seeds. To soften the seed coat to facilitate germination, this method involves submerging the seeds in water for an appropriate duration. Based on the variety and seed lot, the amount of time needed for soaking may differ, but one to two days is usually enough to provide satisfactory results [32].

Vegetative Propagation

Using stem cuttings for vegetative propagation is a practical and effective technique for maintaining some of the unique characteristics of tree species. It also addresses issues with seeds, such as dormancy, germination, viability, and storage, and helps preserve the genetic homogeneity of trees in plantations [33]. However, this approach is hindered by rooting difficulties in many species [34], including *A. senegal,* which has a poor rooting rate [35]. The timing of cutting, the age of the parent plant, and the negative consequences of prolonged exposure to cytokinin are among the factors that influence the success of cuttings in producing plants with developed roots [36].

Earlier studies revealed that stem cuttings for vegetative propagation of the gum arabic tree were feasible but showed limited effectiveness. Badji et al. [37] observed that only stem cuttings taken during the wet season developed roots, and roots were induced only after 8% IBA treatment was applied to the cuttings, with the rooting rate ranging from 50% to 70%. These findings are consistent with those of other investigations done on other Acacia species, such as *A. catechu* [38] and *A. cyanophylla* [39], where IBA treatment improved root formation and development. In a different study, Danthu et al. [40] reported that the time of cutting had a significant impact on *A. senegal* root induction, with the rooting rate ranging from 10% in the dry period to over 70% in the wet period.

Considering the information provided above, it appears that using *in vitro* micropropagation techniques would enable the quick and large-scale multiplication of this commercially and ecologically significant tree.

Micropropagation of Gum Arabic Tree

Micropropagation is the process of growing tiny fragments of plant tissue from a carefully chosen and prepared mother plant and culturing them in a laboratory to create new plants. This method has proven to be effective in the rapid production of many genetically identical plants in a sterile, controlled environment. This approach, which provides a dependable way to propagate valuable or endangered species, has become a cornerstone of plant biotechnology, supporting commercial agriculture, conservation initiatives, and genetic advancement. Various techniques for the micropropagation of gum arabic trees have been documented since the first report on this subject was published in 1973 by Kathju and Tewari [41]. Direct organogenesis, indirect organogenesis, and embryogenesis are the three methods claimed to be used (Table 1 and Fig. 1).

Direct Organogenesis

Direct organogenesis is the method through which plant parts (such as buds, shoots, roots, blossoms, and stems) are created by cell differentiation from adventitious or meristematic tissues without the need for a callus formation step in between [42]. This method is commonly employed for plant micropropagation and is believed to be best suited for ensuring the genetic integrity of regenerated plants [43]. It depends on several variables, including those related to culture and genotype [36]. Usually, latent axillary buds are stimulated to grow into multiple shoots to facilitate rapid *in vitro* reproduction in clonal plants. Growth regulators such as cytokinins or synergistic combinations of cytokinins and auxins are used to awaken, sprout, and multiply dormant axillary buds [44]. After *in vitro* rooting, the regenerated plants are then transferred to a greenhouse for hardening.

Direct organogenesis is the dominant method of gum arabic tree micropropagation, with almost 67% of the published works reporting direct organogenesis (Table 1). Organogenesis is mostly dependent on the kind of explants used and alterations of plant growth regulators (PGRs) in the culture medium, especially for resistant leguminous species [45]. Three different types of explants were used for direct organogenesis: stem cuttings with nodes, nodal segments, and cotyledonary nodes (Table 2). Nodal explants were used in 60% of the reported publications. The most used growth regulators are cytokinins, either alone or in combination with auxins (Table 1). The first report on direct organogenesis was published in 1980, when Dave et al. [46] generated several shoots on stem cuttings with nodes grown on MS media supplemented with different amounts of BA (N6-benzyladenine). The best result (4.0 shoots per explant) was obtained on MS media supplemented with 0.5 mg/L BA. In a different study, stem cutting explants that were cultured on MS media supplemented with IBA (indole-3-butyric acid) only induced roots [37]. Furthermore, gum arabic tree nodal explants exhibited shoot proliferation on MS media supplemented with zeatin alone [47], BAP with varying auxin levels [6, 48-50], BA with NAA [51], or NAA with kin [52]. Nodal explants cultivated on MS media supplemented with combinations of BAP (4.0 mg/L) and NAA (0.5 mg/L) [50] or NAA (0.6 mg/L)

Table 1. Summary of published reports on micropropagation of *Acacia senegal* (chronologically 1973 - 2025).

Explant source	Culture medium/PGRs	Micropropagation pathway	Main findings	Number of shoots per explant/multiplication rate	References [ref. no]
Cotyledonary node	MS + auxin (auxin type and concentration not mentioned)	Indirect Organogenesis	Root primordia emerged from subsets of the callus	N/A	Kathju and Tewari, 1973 [41]
Stem cuttings with nodes	MS + BA (0.5 mg/L)	Direct Organogenesis	Multiple shoot induction	4.0 with BA (0.5 mg/L)	Dave et al. 1980 [46]
Cambial zone tissue	KB+ 2,4-D (2.0 mg/L) + NAA (1.0 mg/L)	Indirect Organogenesis	Callus induction and establishment of cell suspension cultures	N/A	Hustache et al. 1986 [55]
Stem cuttings with nodes	Stem cuttings treated with IBA-8%	Direct Organogenesis	*In vitro* rooting achieved with 8% IBA, the rate of rooting varied between 50 and 70% for leafy cuttings collected in the rainy season	N/A	Badji et al. 1991 [37]
Uninodal explant	MS + Zeatin (5.0 $\times 10^{-5}$ M)	Direct Organogenesis	Multiple shoot induction. Rooting achieved through two stages Induction on MJ + NAA (50$\times 10^{-5}$M) Root extension on a hormone-free medium.	4.0 with zeatin (5.0 $\times 10^{5}$ M),	Badji et al. 1993 [47]
Nodal explant	MS + BA (6.66 µM) + NAA (4.65 µM)	Direct Organogenesis	Multiple shoot induction Rooting conducted on 1/4 MS + IAA (3.0 mg/L) + phytagel (0.2%)	N/A	Gupta et al. 1994 [48]

Cotyledonary node	MS + BAP (1.5 mg/L) + Kin (1.5 mg/L) + NAA (0.5 mg/L) + Ads (25.0 mg/L) + AA (10.0 mg/L) + Gl (146.0 mg/ L)	Direct Organogenesis	Multiple shoot induction. 80% of shoots produce healthy roots when subcultured on 1/4 MS + IAA (3.0 mg/L).	22.0 with BA (3.0 mg/L) and NAA (0.5 mg/L)	Kaur et al. 1996 [49]
Nodal explant	MS + BAP (1.5 mg/L) + Kin (1.5 mg/L) + NAA (0.5 mg/L) + AS (25.0 mg/L) + AA (10.0 mg/L) + Gl (146.0 mg/L)	Direct Organogenesis	Multiple shoot induction Rooting was best on 1/2 MS + IAA (5.0 mg/L).	10.0 with BAP (4.0 mg/L) + NAA (0.5 mg/L)	Kaur et al. 1998 [50]
Nodal segment	MS + BAP (1.0 mg/L) + Kin (0.1 mg/L)	Direct Organogenesis	Multiple shoot induction 25% of the shoots formed roots on MS + IBA (1.0 mg/L) 100% of the shoots formed roots by grafting (with scion length of 3.0 cm and 14-day-old rootstock)	8.3 with BA (1.0 mg/L)	Khalafalla and Dafalla 2008 [6]
Immature cotyledons	MS + 2,4-D (1–3 mg/L) + Kin (0.5 mg/L)	Direct Somatic Embryogenesis	Somatic embryos induced on immature cotyledons explants Somatic germination on MS + BAP (0.22 µM). Profuse rooting was observed during embryos germination	42.0 * with BAP (0.22 µM)	Rathore et al. 2012 [63]
Nodal explants	MS + NAA (0.6 mg/L) + Kin (1.2 mg/L)	Direct Organogenesis	Multiple shoot induction Shoots rooted on ½ MS + IBA (0.5 mg/L).	≅10 with NAA (0.6 mg/L) and Kn (1.2 mg/L)	Khalisi and Al-Joboury 2012 [52]
Nodal segment	MS + 2,4-D (2.0 mg/L) + Kin (0.5 mg/L)	Indirect Organogenesis	Prolific callus formation without shoot regeneration	2.31 with BAP (1.0 mg/L)	Gadzama and Kaldapa 2019 [56]
Hypocotyl Cotyledon	MS + BAP (2.5 mg/L) + Kin (2.5 mg/L) + AS (25 mg/L) + AA (10.0 mg/L) + Gl (146.0 mg/L)	Indirect Organogenesis	Efficient callus induction followed by shoot regeneration Regenerated shoots rooted on ½ MS + IBA (2.5 mg/L) + NAA (2.5 mg/L) + AS (25.0 mg/L)	6.0 with BAP (4.0 mg/L) and NAA (0.1 mg/L)	Gupta P. 2021 [57]
Cotyledonary node	MS + BA (3.0 mg/L) + NAA (0.3 mg/L)	Direct Organogenesis	Multiple shoot induction No root induction	1.44 with BA (3.0 mg/L) and NAA (0.3 mg/L)	Umar et al. 2025 [51]

PGR – Plant growth regulator. MS – Murashige Skoog medium. KB – Knop and Ball medium. MJ – Modified Jordan's medium. BA – N^6-benzyladenine. 2,4-D – 2,4-dichlorophenoxy acetic acid. NAA – α-naphthalene acetic acid. IAA – Indole-3 acetic acid. IBA – Indole-3-butyric acid. BAP – N^6-benzylaminopurine. Kin – Kinetin 6-furfurylaminopurine. AA – Ascorbic acid. Gl – Glutamine. Ads – Adenine sulfate.

* Number of germinating somatic embryos.

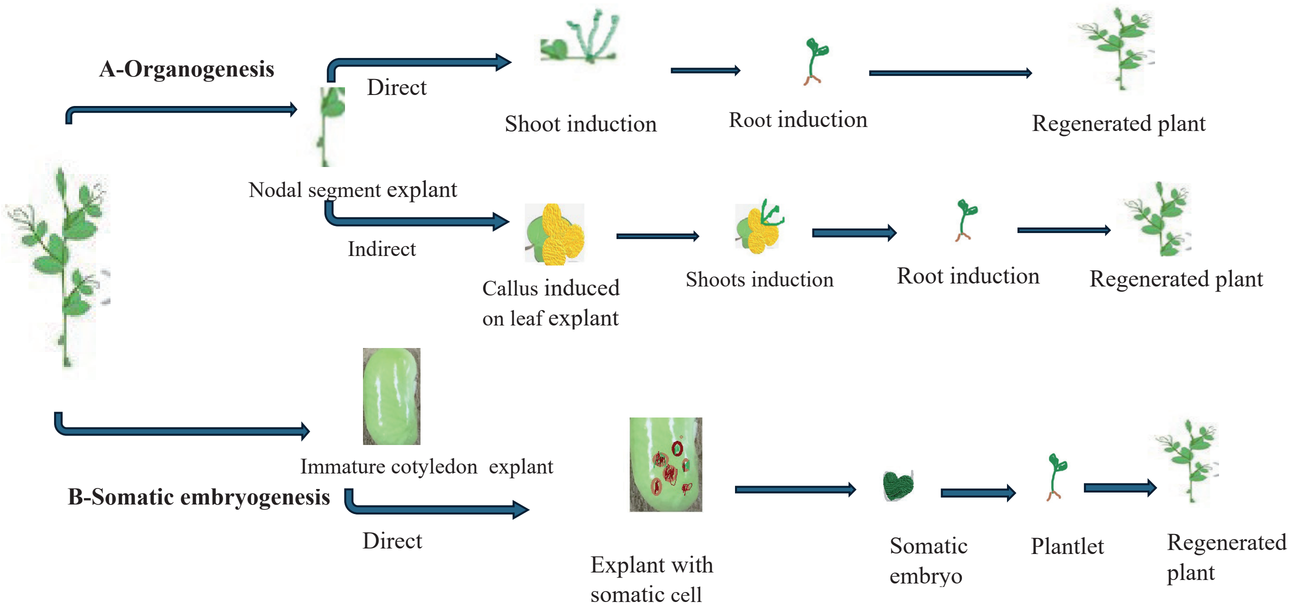

Fig. 1. Different pathways of Acacia senegal micropropagation (A) organogenesis. In the direct pathway, shoots and roots are induced directly on the nodal stem with pre-existing meristems. The indirect pathway induces callus surrounding the wound in a leaf explant, followed by the production of shoots and roots. (B) Somatic embryogenesis. In the direct pathway, the embryonic cell is induced on an immature cotyledon explant, on which somatic embryos grow into shoots and roots.

and Kin (1.2 mg/L) [52] yielded the greatest outcomes for ten shoots per explant. Only two investigations used cotyledonary nodes as explants for gum arabic tree direct organogenesis, when 22.0 shoots per explant were obtained on MS media supplemented with BA (3.0 mg/L) and NAA (0.5 mg/L) [49] or 1.44 shoots per explant were obtained on MS media supplemented with BA (3.0 mg/L) and NAA (0.3 mg/L) [51].

Indirect Organogenesis

Indirect organogenesis is a process of micropropagation utilized in plant cell culture when an undifferentiated mass of cells, known as a callus, gives rise to new organs, such as shoots and roots [53]. Indirect plant regeneration proceeds through stages of embryogenic callus induction and propagation. This approach is more suited for commercial seedling cultivation and large-scale production [54]. Nevertheless, indirect organogenesis of the gum arabic tree has been the subject of very few reports. According to the findings of an initial study carried out by Kathju and Tewari [41], only root primordia were found to arise from subsets of calli acquired from cotyledonary node explants. In another study, after inducing calli on the cambial zone tissue, cell suspension cultures were established [55], and prolific callus was induced

Table 2. Some differences between explants used in *Acacia senegal* direct organogenesis.

Features	Stem cuttings	Nodal segment	Cotyledonary node
Origin / Plant Part	A small section of the stem or shoot that contains a node/s (region where a leaf or branch originates).	A larger piece of stem that includes a node and part of an internode (often 2-3 cm long).	The junction between the cotyledons and the embryonic axis in a seedling (from the germinating seed).
Physiological Stage	Taken from mature or juvenile shoots (often field-grown or in vitro-raised).	Taken from mature stems (semi-hardwood or softwood), sometimes lignified.	Taken from young seedlings (usually 5-10 days old).
Meristematic Activity	Contains axillary bud meristems that can directly form new shoots.	Contains axillary buds but may have more differentiated tissues.	Contains highly active meristematic tissues at the cotyledonary junction, giving strong regenerative potential.
Common Use in Micropropagation	Frequently used for direct shoot organogenesis or axillary bud proliferation.	Often used for vegetative propagation (rooting of cuttings), not always for tissue culture.	Common in in vitro cultures for initiating multiple shoots from juvenile tissues.

on the nodal segment without shoot regeneration [56]. Efficient indirect organogenesis for gum arabic trees was obtained in only one report [57], when Gupta (2021) observed that all types of explants, including leaflets, rachis, hypocotyl, and cotyledon explants, showed signs of callus induction. However, only the cotyledons and hypocotyls were optimal for robust and healthy callus growth when cultured on MS medium enhanced with 2,4-D (2.5 mg/L), AA (10 mg/L), BAP (0.5 mg/L), and AS (25 mg/L). Following the transfer to regeneration medium, shoot bud regeneration media supplemented with BAP (2.5 mg/L), Kin (2.5 mg/L), AS (2.5 mg/L), AA (10.0 mg/L), and glutamine (146.0 mg/L) showed the highest degree of shoot bud development (6.0 shoots per explant). Before rooting, shoots were further elongated on MS medium supplemented with BAP (0.5 mg/L) + Kin (0.5 mg/L), and similar amounts of adenine sulfate and glutamine were used in regeneration media.

Somatic Embryogenesis

Somatic embryogenesis is a micropropagation method in which somatic cells generate embryogenic cells under the appropriate inductive conditions. These cells then undergo several morphological and biochemical changes to form a structure without fertilization and go through stages comparable to those of a zygotic embryo, called a somatic embryo [58].

Like organogenesis, somatic embryogenesis has two pathways: producing somatic embryos either directly from individual somatic cells or from embryonic calli indirectly [59].

It is widely acknowledged that somatic embryogenesis is a superior approach for plant micropropagation because, by definition, it produces more regenerated plants than the organogenesis pathway [60]. Therefore, somatic embryogenesis may be a good option for the commercial production and bulk replication of threatened crop species such as gum arabic trees [61].

Generally, direct somatic embryogenesis occurs when single cells or tiny cell clusters on the explant surface develop into new embryos without the need for a callus phase [58]. The lack of a callus phase, which is a major cause of somaclonal variation, genomic change, albinism, and sterility, is the primary advantage of direct somatic embryogenesis over indirect somatic embryogenesis [62]. Under optimum conditions, somatic embryos develop into shoots and roots (Fig. 1b)).

In the case of the gum arabic tree, only direct somatic embryogenesis was documented when Rathore et al. [63] examined the factors influencing somatic embryogenesis from immature cotyledons. Explant type and medium components, specifically GR levels and amino acid supplementation to the medium, have the greatest impact on this process (Table 3). It was reported that only cotyledon explants derived from immature seeds were able to induce somatic embryos on induction media. This could be due to their advantageous physiological composition at this developmental stage.

Table 3. Stages *of Acacia senegal* somatic embryogenesis, culture conditions, duration and biological responses associated with each stage.

Stage	Basal Media and GRS	Duration (Approx.)	Remarks
Explant source	MS +2, 4-D (0.45 μM) + Kin (2.32 μM) + L-glutamine (15 μM)	0	– Only cotyledon explant isolated from immature seeds can produce somatic embryos.
Early stage of somatic embryo induction	MS +2, 4-D (0.45 μM) + Kin (2.32 μM) + L-glutamine (15 μM)	2-3-week-old cultures.	– Explant swelling – Globular embryos appear on the surface of explants
Expression stage (Early development of globular, heart and torpedo)	MS +2, 4-D (0.45 μM) + Kin (2.32 μM) + L-glutamine (15 μM))	4-5-week-old cultures.	– Somatic embryos were induced only on medium containing low concentrations (0.45-4.52 μM) of 2, 4-D. – The frequency and intensity of somatic embryogenesis were enhanced significantly by the addition of L-glutamine in optimized induction medium (MS + 0.45 μM 2, 4-D + 2.32 μM Kin).
Maturation (Cotyledonary stage)	MS +2, 4-D (0.45 μM) + Kin (2.32 μM) + L-glutamine (15 μM))	4–-8 weeks (Maturation stage)	– L-glutamine (15 mM) is important for maturation – About 60% somatic embryos were found to be cotyledonary and torpedo staged types
Somatic embryo germination stage (conversion to plantlet)	MS + BAP (0.22 μM)	2-3 weeks of transfer on medium containing BAP	– Most embryos lost their germination potential and died if they continued to be on the same development and maturation medium for a longer duration. – The appearance of a leaflike structure (and root initiation were observed on medium containing low concentration of BAP).

Immature cotyledons cultured on MS medium enhanced with 15 mM L-glutamine, 0.45 μM 2,4-D, and 2.32 μM kin produced the best results for somatic embryogenesis. Most embryos matured only on media containing 15 mM L-glutamine, which is essential for somatic embryo development. The best result (42 germinating embryos per explant) was obtained on medium supplemented with 0.22 μM BAP (Table 1).

In vitro Rhizogenesis of Regenerated Shoots

The ability of regenerated shoots to induce roots is the most crucial step in micropropagation. Several elements, including culture medium, PGRs, and their concentrations, all affect the development of roots from regenerated shoots [36]. In general, high auxin levels are needed for root induction, and they play a key role in controlling root growth, especially indole-3-acetic acid (IAA) and indole-3-butyric acid (IBA) [64]. High rates of *in vitro* rhizogenesis were seen for gum arabic trees when auxin IBA was used at varying doses. Stem cuttings treated with 8% IBA gave a 70% rooting rate [37]. In another study, a high rooting rate was obtained on ½ MS medium containing 0.5 mg/L of IBA [52]. Khalafalla and Dafalla [6] reported that only 25% of the *A. senegal* shoots gave roots on MS media enhanced with 1.0 mg/L of IBA. Because of their complementary effects on rooting, IBA and NAA are frequently utilized in combination. This is because NAA encourages cell division and differentiation, while IBA boosts the creation of root primordia [65]. This combination increases the expression of genes involved in root formation [66]. Accordingly, Gupta (2021) [57] reported excessive rooting for *A. senegal* shoots cultured on ½ MS supplied with IBA (2.5 mg/L) in combination with NAA (2.5 mg/L). Furthermore, healthy roots were obtained for *A. senegal* when induced shoots were cultured on low-strength MS medium enhanced with IAA at either 3.0 mg/L [49] or 5.0 mg/L [50]. Numerous facets of plant growth and development are influenced by auxin and cytokinin. Early phases of somatic embryogenesis establishment and post-embryonic plant development are regulated by auxin [67]. By altering the auxin/cytokinin ratio, Skoog and Miller [68] were able to show how callus tissues developed into roots and/or shoots. Since then, explants of hundreds of distinct species have undergone somatic embryogenesis through variations in this ratio [69]. Likewise, direct somatic embryogenesis in the gum arabic tree produced roots on the same medium when it was grown on a medium containing BAP at a low concentration (0.22 μM) [63].

Plantlet Acclimatization

Acclimatization, or plantlet adaptation to climatic or environmental conditions outside laboratories, is the final stage of this vegetative propagation process [70]. This stage is especially vulnerable to failure because of variations in light, humidity, and nutrient availability. The acclimatization of gum arabic tree plants cultivated by micropropagation has only been the subject of a few published studies, and the findings have been inconsistent. Badji et al. [47] reported that a 100% survival rate was observed in a greenhouse when plantlets were transferred to pots filled with a 3:1 sterile vermiculite and sand. Conversely, Gupta [57] found a low survival rate (40-50%) with the same mixture and ratio.

Discussion

Despite the substantial socioeconomic, ecological, and medicinal advantages of gum arabic, its micropropagation has received relatively little attention. To maximize its efficacy, several challenges and restrictions need to be overcome. The challenges include a low rate of multiplication, tissue necrosis and browning, poor rooting ability, and a high rate of plantlet mortality when transferred from the laboratory to the soil. These difficulties often arise during micropropagation. Likewise, gum arabic production areas, which are mainly African countries, also face problems such as inadequate technical expertise, limited funding, limited access to dependable energy and laboratory supplies, and poor infrastructure. Additionally, creating central laboratories and encouraging cooperation between businesses, academic institutions, and research centers may be the way to overcome the high costs and the need for specialized knowledge, infrastructure, and skills required for cutting-edge methods like somatic embryogenesis.

Micropropagation provides a quick way to generate clonal planting material for afforestation and elite germplasm conservation. Future work should focus on increasing the feasibility of gum arabic tree micropropagation by streamlining culture processes, such as the use of transient immersion bioreactors and less costly alternatives for producing culture media. The viability of bioreactor-based micropropagation for large-scale in vitro plant production in horticulture and medicinal plants has already been demonstrated [71]. Another innovative strategy is to incorporate machine learning (ML), which has become a revolutionary tool for micropropagation, enabling data-driven optimization of complex biological systems, forecasting, and enhancing a variety of *in vitro* outcomes, including root induction, shoot regeneration, growth media optimization, sterilization protocol design, stress response prediction, and growth performance modeling under abiotic stressors [72]. Additionally, by anticipating the optimal mix of culture conditions to maximize growth or regeneration, researchers and commercial operations can improve efficiency, precision, and reproducibility by incorporating artificial intelligence (AI) into tissue culture workflows [73]. In laboratory settings, this data-driven optimization can boost growth rates, lower contamination, and increase productivity, particularly for intricate procedures like somatic embryogenesis.

Furthermore, this review's somatic embryogenesis methodology offers a promising way to improve gum arabic tree breeding initiatives. Somatic embryogenesis enables targeted genetic modifications for developing gum arabic tree cultivars with enhanced traits such as stress tolerance, disease resistance, and improved yield and quality. This could be made possible by combining somatic embryogenesis with modern biotechnology techniques like RNA sequencing, metabolomics, and genome editing tools like CRISPR/Cas9.

Conclusions

Commercial gum Arabic production necessitates planting material that is genetically homogeneous, physiologically robust, and pathogen-free. Seed propagation, which is presently the most common method in sub-Saharan African countries, produces a varied range of progeny due to the gum arabic tree's high incidence of outcrossing, self-incompatibility, and cross-pollination. These concerns have a negative impact on gum quality, drought resilience, and production. Micropropagation, which allows for large-scale production of gum arabic trees, is a viable solution to these issues.

Despite the socioeconomic and ecological benefits of the gum arabic tree in sub-Saharan African countries, micropropagation has received relatively little attention. This is due to several challenges, including a low rate of multiplication, poor rooting ability, difficulties in acclimatization, inadequate technical expertise, limited funding, limited access to dependable energy and laboratory supplies, and poor infrastructure for mass propagation. Multidisciplinary collaboration between businesses, academic institutions, and regulatory authorities will provide solutions to these challenges, strengthening and scaling these technologies and paving the way for the forest sectors in producing countries to access resilient, disease-free, and high-quality planting material to further support growers' productivity, sustainability, and economic viability.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

The author would like to thank the Institute of Scientific Research and Revival of Islamic Heritage at Umm Al-Qura University (Project # 43409065) for financial support.

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