# *BOSWELLIA PAPYRIFERA* (FRANKINCENSE) TREES IN ETHIOPIA AND ERITREA: REVIEW

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## ABSTRACT

The *Boswellia papyrifera*, a deciduous tree species vital for frankincense production, is indigenous to the drylands of Africa, particularly Eritrea and Ethiopia. This review consolidates existing research to examine the distribution, regeneration challenges, and threats con-fronting this ecologically and economically significant species. Despite its multifaceted roles in providing frankincense, fodder, and ecological services, *B. papyrifera* populations are experiencing a notable decline. Factors contributing to this include the expansion of agricultural activities into woodland areas, unsustainable tapping practices for resin extraction, excessive grazing, and the increasing impacts of climate change. Overharvesting, in particular, significantly impedes natural regeneration, resulting in a population structure dominated by mature trees. The ecological functionality of *B. papyrifera* in combating desertification is also under threat. Thus, the implementation of sustainable management strategies such as regulated tapping practices, controlled grazing, and the exploration of ex-situ conservation methods are urgently needed. Given their historical and cultural significance, the Orthodox churches of Ethiopia and Eritrea, which utilize frankincense in religious ceremonies, could play a pivotal role. Their involvement in promoting sustainable harvesting, establishing protected areas, and conducting reforestation initiatives could significantly contribute to the long-term viability of *B. papyrifera* and the preservation of the livelihoods that depend on it.

**Keywords:** *B. papyrifera* uses, Frankincense (Gum & Resin), major factors, conservation & restoration measures, climate change

## INTRODUCTION

*Boswellia papyrifera* (Del.) Hochst or simply *Boswellia papyrifera*, a multipurpose deciduous tree native to the Horn of Africa, particularly Ethiopia and Eritrea, is renowned for producing frankincense, a valuable oleo-gum resin harvested from its bark. This species thrives in the drylands, offering significant ecological and socioeconomic benefits, including desertification control and income generation for local communities. While its importance is widely acknowledged, *B. papyrifera* populations are facing a decline due to factors such as overharvesting, grazing, and agricultural expansion. Consequently, its status as an endangered species in East Africa necessitates urgent conservation attention.

This review aims to synthesize existing knowledge regarding the current contribution of *B. papyrifera*-dominated woodlands and the challenges hindering their regeneration. Specifically, it seeks to address the following knowledge gaps: the ecological, climatic, and biological conditions influencing the species in Eritrea and Ethiopia; its geographical distribution and current population status; the diverse uses of the tree and the major factors contributing to its decline; and evidence-based recommendations for its sustainable utilization, restoration, and conservation in the region. By addressing these questions, this review intends to provide a comprehensive understanding of the current state of *B. papyrifera* and inform future management and conservation strategies.

This review distinguishes itself by providing a comprehensive and up-to-date synthesis of the multifaceted challenges confronting *Boswellia papyrifera* across its primary distribution range in Ethiopia and Eritrea. Unlike previous studies that may have focused on specific aspects or geographical areas, this work uniquely integrates ecological, socio-economic, and cultural dimensions to offer a holistic understanding of the species' decline. Furthermore, it explicitly highlights the critical bottleneck of regeneration failure as a central threat and underscores the limitations of current research methodologies and conservation approaches. Notably, this review breaks new ground by emphasizing the untapped potential of engaging influential local institutions, such as the Eritrean and Ethiopian Orthodox churches, in conservation efforts, leveraging their cultural authority and vested interest in frankincense as a unique pathway toward sustainable management and restoration.

## METHODOLOGY

This review was compiled through a process of critical analysis and discussion, considering diverse perspectives on opposing viewpoints, theories, and methodologies related to *Boswellia papyrifera*. To gather relevant literature, a systematic online search was conducted across international scientific databases, including Scopus, Web of Science, and Google Scholar. The primary keywords used for this search included "*Boswellia papyrifera*", "frankincense", “ecological/ climatic/ biological/ geographic conditions”, "regeneration/ population status", “uses", "threats/ factors", “conservation/ restoration", "Ethiopia", and "Eritrea". The search focused on literature published currently between 2000 and 2024 to capture contemporary research on the species; however important old publications before 2000 were also considered. The selection of literature for this review followed specific inclusion and exclusion criteria. Included studies focused on the ecology, distribution, regeneration, threats (such as agricultural expansion, overharvesting, grazing, and climate change), uses, and conservation efforts related to *B. papyrifera* in Ethiopia and Eritrea. Literature discussing other *Boswellia* species without specific relevance to *B. papyrifera* in the Horn of Africa, purely chemical analyses of frankincense without ecological context, or studies outside the specified time frame were excluded.

The critical analysis involved evaluating the methodological rigor, sample sizes, and consistency of findings across different studies. For instance, studies reporting on regeneration rates were compared based on their assessment techniques (e.g., seedling counts in quadrats, population structure analysis using diameter at breast height), and discrepancies in reported trends were noted and discussed in the context of varying environmental conditions and research methodologies. The reliability of cited studies was prioritized by focusing on peer-reviewed journal articles, reputable academic books, and well-documented thesis works from recognized institutions. This systematic approach ensured a comprehensive and critically evaluated synthesis of the existing knowledge on *Boswellia papyrifera*.

## RESULTS

### Background Information about Boswellia papyrifera

*Ecology*

The indigenous multipurpose tree *B. papyrifera* covers more than 1.5 million hectares in Ethiopia and Eritrea with an average temperature of 20-27 °C or 25-40 °C and annual rainfall fewer than 900 mm or 100-800 mm; it is mostly found on degraded dry plains 950-1800 m above sea level (Morka, 2024; Ogbazghi *et al*., 2006). It grows on degraded sites with sandy river basins and valleys, lava flows, steep rocky slopes, and very shallow soils. *B. papyrifera* is found in Acacia-Commiphora woodlands and has a variety of vegetation relationships (Worku *et al*., 2018). The ecological distribution of *B. papyrifera* is limited to lowlands that experience hot and dry conditions. *B. papyrifera* is mostly found in Eritrea between 800 and 1850 meters above sea level, with its growing season lasting between 45 to 100 days, and its annual rainfall ranging from 375 to 700 mm (Ogbazghi *et al*., 2006). Although a lower elevations, a higher air temperature, a short length of the rainy season, and high evapotranspiration lowers the soil moisture status, they also had advantages. Thus, the climatic parameters could not be regarded as the only absolute limits (Ogbazghi *et al*., 2006).

*Biology*

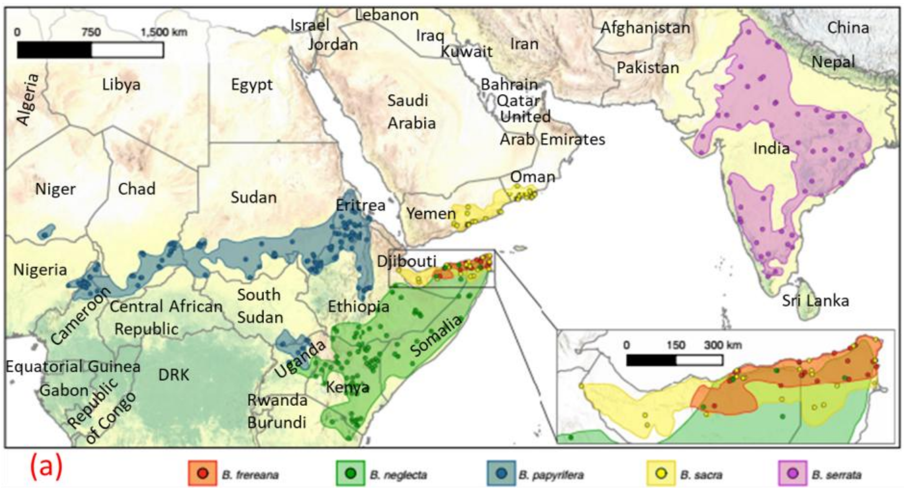
Boswellia papyrifera is a member of the Burseraceae family, which has 17 genera and up to 600 species (Abiyu *et al*., 2006). There are six species of Boswellia in Ethiopia: *B. papyrifera*, *B. neglecta*, *B. microphylla*, *B. ogadensis*, *B. rivae*, and *B. pirrotae*. All known species of Boswellia found in Ethiopia, except *B. pirrotae*, are currently harvested for gum-olibanum; the main source of frankincense produced in Ethiopia is *B. papyrifera* (Lemenih *et al*., 2004). *B. papyrifera* trees in the Horn of Africa might grow up to 14–16 meters tall and have a maximum diameter at breast height of 51.5 cm. The area is one of the primary locations for the growth of Boswellia, and frankincense is commercially extracted there (Eshete *et al*., 2005). This species is a tiny deciduous tree with a spherical crown, strong branches capped with clusters of leaves, and noticeable vertical resin ducts in the bark. It is known for species that bear oleo-gum resins (Tatek *et al*., 2016).

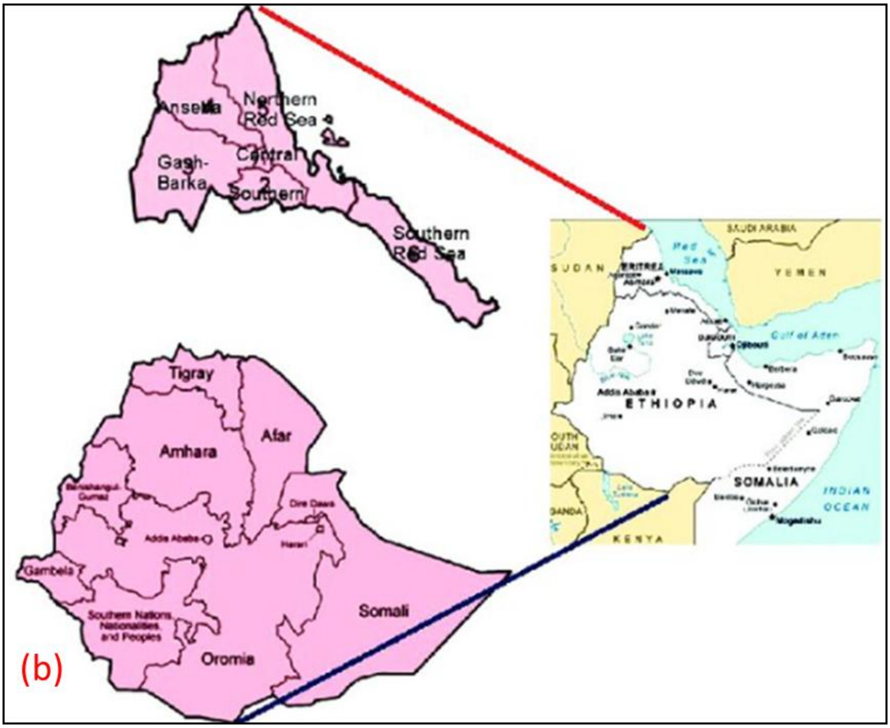
The tree *B. papyrifera* mainly or primarily reproduces sexually (through seeds) and grows back from its seeds naturally (Rijkers *et al*., 2006). Within the species, seed establishment may vary and seems to be a limiting factor. Insect infestation or a mechanism to improve pollination may be the cause of flower sterility. Fruit-set is minimal during open pollination, at roughly 10 %. When the embryo reaches maturity, endosperm is absent (Sabo *et al*., 2022). It has strong, rigid branches with spherical crown leaves and clusters at the tips. The species flowers in October and begins to shed at the beginning of December, while some trees keep their flowers for a considerably longer period. It produces leaves during the rainy season, which can occur in April (Tatek *et al*., 2016). With 11–29 pinnate leaflets, pubescent surfaces, and petioles that are 0.5–4 cm long, its leaves are 15–45 cm long. The flower typically consists of ten yellow stamens, five petals measuring 5–8 mm in length, and a long red peduncle (flower stalk) that can reach up to 35 cm. The slash is red-brown and emits a fragrant resin, while the bark is yellowish to pale brown and peels off in huge flakes. Schizogenous oleo-gum-resin pockets can be found in the bark (Dharani, 2011). The resin of *Boswellia papyrifera* contains approximately 5–9 % essential oil, 40–60 % boswellic acids, 20–30 % polysaccharides, and 13–17 % resin acids (Khan *et al*., 2016). Resin production typically begins when the tree reaches 8 to 10 years of age or when its trunk attains a diameter of about 38 cm at breast height (Paramanik *et al*., 2012). The age or life expectancy of a Boswellia tree varies by species; for instance, the age of *B. pirottae* is estimated to be 10-15 years, and for *B. ovalifoliolata*, 20-30 years (Bhakshu *et al*., 2023; CoP18 Doc. 66, 2019). According to Tilahun (1997), a Boswellia tree will produce incense even until 50 to 60 years. The phonological cycle of the species is mainly controlled by the distribution of precipitation (Mokria *et al*., 2017; CIFOR-ICRAF, 2011).

*Geographical Distribution*

In Ethiopia, *B. papyrifera* is found in the dry Combretum-terminalia broad-leaved deciduous woodlands of the north and northwest, and some of the country's largest river gorges in the north (Worku *et al*., 2018). The *B. papyrifera* dominated woodland was primarily found in Benishangul-Gumuz, Gambella, Oromiya, Amhara, and Tigray regions of Ethiopia (the blue colors in Fig. 1 show *B. papyrifera*). Available estimates show that approximately 1.7 million hectares of woodlands with *B. papyrifera* as their main species composition currently occur in three regional states: Amhara, Benishangul-Gumuz, and Tigray. At the moment, the species is primarily found and widely used in Tigray (940000 ha) and Amhara (604000 ha) (Worku *et al*., 2018). It can be found in drier parts of Africa, from Ethiopia and Eritrea in the east to Nigeria in the west of Africa. Ethiopia, Somalia, and Eritrea are where it is most common (Alemu *et al*., 2012). With an altitudinal range of 600–1800 m above sea level, the Boswellia predominated woodland, which is part of the *Combretum Terminalia* deciduous woodlands of Ethiopia's dry forests, forms the largest vegetation cover and is found in five regional states: Benishangul-Gumuz, Gambella, Oromiya, Amhara, and Tigray. Fig. 1 below illustrates the ranges of *B. papyrifera* tree species, along the other Boswellia species, in several countries with varying climatic and geographic conditions.

**Fig. 1: Distribution of *Boswellia* tree species (*B. frereana, B. neglecta, B. papyrifera, B. sacra, and B. serrata*) around the world (Bongers *et al*., 2019) (a). Location of Eritrea and Ethiopia in the Horn of Africa and country maps showing major administrative divisions (Source: Wilson, 2020) (b).**






**Population Status**

Several population studies of *B. papyrifera* across different geographic regions indicate that the population is primarily composed of mature trees. Seedlings and saplings are either absent or present in very low numbers, pointing to a serious deficiency in natural regeneration. This lack of recruitment suggests the population is unstable in Ethiopia and Eritrea (Eshete *et al*., 2005; Ogbazghi *et al*., 2006). Research on the regeneration status of *B. papyrifera* reveals poor seedling establishment in its native habitat (Ogbazghi, 2001; Gidey *et al*., 2020). The regeneration issue is underscored by the fact that the majority of the current population consists of mature trees. For instance, in Northern Ethiopia, nearly 76 % of the existing *B. papyrifera* trees have a diameter at breast height (DBH) greater than 30 cm (Derero *et al*., 2018). If this trend continues, there will be no replacements, and the species is likely to face extinction once the current mature trees are depleted.

When evaluating the condition of tree species in a specific forest region, indicators such as density and regeneration status are commonly used. An analysis of the population structure of *B. papyrifera* revealed a notable presence of individuals in the smaller diameter classes. Some studies, such as those by Eshete *et al*. (2005) in Metema (Ethiopia) and Ogbazghi *et al*. (2006) & Rijkers *et al*. (2006) in Eritrea, reported similar structural patterns. These studies consistently show that individuals in the lower-diameter classes are under-represented, while those in the larger-diameter classes are over-represented. This skewed stem diameter distribution suggests a lack of recent regeneration, highlighting a serious long-term threat to the species' survival. The natural population of *B. papyrifera* is declining, primarily due to factors such as excessive harvesting, overgrazing, fire, shifting cultivation, poor incense tapping practices, termite damage, and other insect infestations as described in detail in Chapter - Uses of *Boswellia papyrifera*.

**Uses of *Boswellia papyrifera***

From an ecological, social, and religious standpoint, *B. papyrifera* is one of the most significant multipurpose deciduous tree species in Ethiopia and Eritrea. Frankincense, the most important product of *B. papyrifera,* frankincense, has been gathered for a variety of conventional and commercial uses, including liqueurs, detergents, creams, fragrances, medicine, cosmetics, and beverage flavoring (Lemenih & Teketay, 2003). In addition to being employed in the international pharmaceutical, food flavoring, and perfume sectors, frankincense is also chewed, used in coffee ceremonies, and used as traditional medicine by people in northeast Africa. Essential oils derived from *B. papyrifera* gum are utilized in the perfume industry, in the production of paints and varnishes, and as a laxative in the medicinal sector (Ogbazghi, 2001).

Despite its many uses, *B. papyrifera* has not been domesticated yet. In woods, gum is collected from trees that grow naturally (Ogbazghi *et al*., 2006). Gum collecting and commercialization remain concessionaires' sole rights since the implementation of the concession system in Ethiopia and Eritrea (Tadesse *et al*., 2020; Lemenih & Kassa, 2011). The numerous uses of *B. papyrifera* and its products, especially frankincense, in the fields of ecology, socioeconomics, and medicine are thoroughly examined in this section.

*Ecosystem Services*

*B. papyrifera* grows on rocky and dry areas where other trees usually fail, including on steep slope gradients reaching 40 %, and this ability helps to improve degraded areas and provides economic and social benefits by giving plant cover, biomass, shade, and soil protection (Gebrehiwot *et al*., 2003). Its ability to grow under harsh soil and climatic conditions has made it the most qualified choice for combating desertification, rehabilitation of degraded drylands, and community adaptation to plausible climate change impacts (Lemenih & Teketay, 2004; Eshete *et al*., 2012). The leaves and seeds of the ecologically significant *B. papyrifera* tree are highly valued as dry-season feed for camels and other livestock, and almost every part of the tree serves a specific purpose (Gebrehiwot *et al*., 2003). The fragrant blooms that emerge as the tree sheds its leaves are important sources of nectar for honey bees. Due to its ability to thrive in arid climates and nutrient-deficient soils, *B. papyrifera* is among the top candidates for restoring degraded drylands and strengthening the resilience adaptation, and mitigation of climate change in dryland communities (Worku & Bantihun, 2018; Ogbazghi *et al*., 2006).

*Socioeconomic Uses*

*Boswellia papyrifera* and other gum and resin-producing trees, such as *Acacia, Boswellia,* and *Commiphora* species, have real and potential socioeconomic and environmental significance for local communities and merchants because they have created a large number of job opportunities. After all, gum and resin or incense products have been sold for cash income in both domestic and foreign markets. The gum known as frankincense or "olibanum" is used for commercial purposes, while the wood stem of *B. papyrifera* is used for poles and lumber in Ethiopia and Eritrea, its leaves for fodder, and its flowers for beekeeping. The stem, leaves, and seeds of *B. papyrifera* are highly valuable as feed for livestock, including goats, camels, and others. The light and rather soft stem wood of *B. papyrifera* is used for plywood, picture frames, veneers, matchboxes, pencils, and furniture (Gebrehiwot *et al.*, 2003; Zinaw, 2012). Rural populations employ *B. papyrifera* wood for poles and timber, and it is also used to a lesser extent in the industrial production of wooden goods such as plywood, boards, and matchboxes (Ogbazghi, 2001). *B. papyrifera's* pink-scented flowers are used by honeybees for pollen and nectar, especially during the extended flowering season from October to February, which is ideal for starting a bee colony that has been often of a high quality (Gebrehiwot *et al*., 2003).

Off-farm employment opportunities such as incense collection are accessible to both male and female rural farmers. In northern Ethiopia, while men predominantly engage in the tapping and collection of incense, women contribute significantly by sorting and grading the product. A taper can earn approximately 100–150 USD by harvesting 1,000–1,500 kg of incense, whereas women involved in off-farm incense-related work can earn an average of 160 USD over ten months (Gebrehiwot *et al*., 2003; Aregawi, 1997; Tilahun, 1997; Alemu *et al*., 2015). For example, in 2024 on average one kilogram of good quality incense in Ethiopia was sold with 12-20 USD or 1000-1600 ETB assuming 1 USD = 82 ETB (https://www.exchange-rates.org/exchange-rate-history/usd-etb-2024). In 2024, the price of incense in Ethiopia was ten times more expensive than sugar (100-150 ETB per kilogram).

*Religious Uses*

*Boswellia papyrifera* is said to be the source of the ancient frankincense, which has been used for millennia in a variety of religious rituals. Its scent is thought to improve meditation and spiritual experiences (Fatima *et al*., 2024; Ogbazghi *et al*., 2006). From ancient Egypt (3000 BC) to modern applications (1600 AD to present), frankincense resin has been used extensively for burning incense (Fatima *et al*., 2024). Frankincense has been used in religious rituals across various cultures since ancient times, when the Romans and Greeks, respectively, connected frankincense with sacrifice in the second and sixth centuries BC (Göttsch, 1986). Currently, frankincense continues to play a central role in church ceremonies and religious practices around the world.

In Ethiopia and Eritrea, incense has been used in religious ceremonies since at least the time of the powerful Aksumite emperors around 500 BC (Goldschmidt, 1970), and its use continues today in the Orthodox Church.

The Holy Bible describes frankincense as a sacred substance offered to God in worship (Exodus 30:34), and it was also one of the three gifts presented by the Magi to the infant Jesus (Matthew 2:11). Frankincense was commonly burned during religious rituals in churches, tabernacles, and temples to produce a fragrant smoke symbolizing prayers rising to heaven (Revelation 8:4). This tradition dates back to early Christianity and remains a practice in many of the world’s largest and oldest Orthodox and Catholic churches. For instance, in Ethiopia, it is estimated that over 2 million kilograms of frankincense are used annually by more than 15,000 churches; an average of 150 kilograms per church each year (Tilahun, 1997; Worku *et al.*, 2011; CoP18 Doc. 66, 2019; CoP18 Doc. 25, 2020). In the last ten years, the number of churches in Ethiopia increased significantly along with the increasing trend of the population. Assuming that 2M kg of frankincense had been used by Ethiopian churches in 2024, the corresponding monetary value would have been 24M-39M USD. The use of frankincense in Ethiopian and Eritrean Orthodox churches was increasingly observed during the Coronavirus 2019 (COVID-19) respiratory disease pandemic in 2020. The churches potentially used frankincense smoke as a significant therapy to improve respiratory health and prevent COVID-19. This proves the vital importance of frankincense in economy, religioun, and medicine in Ethiopia and Eritrea.

*Medicinal and Traditional Uses*

*B. papyrifera* is widely used in traditional medicine in Ethiopia and Eritrea. The gum of *B. papyrifera* is occasionally chewed to relieve thirst, while its resin is traditionally used as a febrifuge. The roots and leaves are applied in the treatment of lymphadenopathy (swollen lymph nodes), and the bark is chewed to alleviate stomach disorders. Additionally, when the resin is burned, it functions as a mosquito repellent in tropical regions (Ogbazghi, 2001; Gebrehiwot *et al*., 2003). These traditional applications are evidence of the cultural and medicinal significance of the species throughout the region. The uses of *B. papyrifera* are summarized as shown in Table 1.

**Table 1: Summary of the Uses of *Boswellia papyrifera* (Frankincense Tree)**

| Category | Uses | Examples (with citations) |
|---|---|---|
| **Ecosystem Services** | Dry-season fodder (leaves, seeds); Nectar for bees (flowers); Grows in degraded, arid, rocky areas; Used for restoring drylands and combating desertification; Soil protection and biomass production | Thrives on steep slopes up to 40%, poor soils (Gebrehiwot et al., 2003); Supports climate resilience in dryland communities (Worku & Bantihun, 2018; Eshete *et al.*, 2012); Ecological restoration (Ogbazghi *et al.*, 2006) |
| **Socioeconomic** | Frankincense production and trade (domestic & international markets); Poles, lumber, plywood, veneer, furniture (wood); Off-farm employment (tapping, sorting, grading); Beekeeping (flowers); Income generation from resin collection | Income: Tappers earn \$100–150 per 1000–1500 kg (Gebrehiwot *et al*., 2003); Women earn ~\$160 in 10 months (Aregawi, 1997; Alemu *et al*., 2015); 1 Kg of incense is > 7 times expensive than 1 Kg of sugar. |
| **Religious** | Frankincense is used in ancient and modern religious rituals; Burned in churches for spiritual symbolism (e.g., prayer smoke); and Integral to Orthodox and Catholic ceremonies. | Used in Egypt since 3000 BC (Fatima *et al*., 2024); Aksumite use since 500 BC (Goldschmidt, 1970); Biblical use: Exodus 30:34; Matthew 2:11; Revelation 8:4; 2 million kg used annually in 15,000 churches (Tilahun G., 1997) |
| **Medicinal & Traditional** | Chewed to relieve thirst (resin)- Used as a febrifuge; Treats lymphadenopathy (roots/leaves); Bark chewed for stomach issues; Burned as a mosquito repellent. | Traditional medicine in Ethiopia and Eritrea (Ogbazghi, 2001; Gebrehiwot *et al*., 2003) |
| **Commercial/ Industrial** | Used in liqueurs, detergents, creams, cosmetics, beverages, pharmaceuticals- Source of essential oils for perfumes, paints, varnishes | Applications in global food, cosmetic, and pharma industries (Lemenih & Teketay, 2004; Coppen, 1995); Oils used in perfumes and laxatives (Ogbazghi, 2001) |

## Major Disturbances (Negative Factors) for the Decline of *Boswellia papyrifera*

### *Deforestation and Expansion of Farming in the Woodland*

Environmental concerns have been raised due to the decline of *Boswellia papyrifera* populations in eastern Africa. Strong evidence suggests that populations of *B. papyrifera* in Ethiopia (Abiyu *et al.*, 2010; Worku & Bantihun, 2018) and Eritrea (Ogbazghi *et al.*, 2006) have significantly decreased in recent decades. It is believed that both resettlement and spontaneous immigration (Lemenih & Teketay, 2003), particularly from the highlands, are major contributors to the degradation of *Boswellia*-dominated woodlands. The fertile soil and favorable climate in these countries, ideal for growing cash crops like cotton and sesame, brought large numbers of immigrants. These populations often engage in extensive land cultivation, leading to widespread land grabbing. In the areas where the ecological zone is optimal for growing cotton and sesame, farmers clear *Boswellia* forest for agricultural use in the belief that cotton and sesame are more profitable. Groenendijk *et al*. (2012) predict that if harvesting continues at its current rate, the yield of *B. papyrifera* in Ethiopia will decline by 50 % within the next 15 years, and the population will decrease by 90 % over the next 50 years. Over the past 20 years, more than 177,438 hectares of *B. papyrifera* forest have been lost in Northern Ethiopia (Gebrehiwot *et al*., 2002). In the late 1970s, *B. papyrifera* covered over 510,000 hectares of land in Tigray (Tilahun *et al*., 2011).

*Extensive Tapping and Overexploitation*

Tapping has been shown to reduce both seed viability and yield of frankincense in *Boswellia papyrifera* (Rijkers *et al*., 2006). The practice negatively impacts the species in several ways, primarily by producing non-viable seeds when tapping becomes excessive. In multiple countries where *Boswellia* species are found, poor harvesting practices such as year-round over-tapping have led to long-term population declines (Negussie *et al*., 2021).

In Ethiopia and Eritrea, the trees are being increasingly overexploited to meet the growing global demand for frankincense. Inappropriate tapping techniques, such as deep or overly long incisions (girdling), further exacerbate the damage (Abiyu *et al*., 2010; Mengistu *et al*., 2012). One of the main indicators of overexploitation is the absence of juvenile and sapling classes in populations. High mortality among mature trees, combined with the scarcity of young individuals, points to a serious decline in regeneration across the species' range (Bongers *et al*., 2019; Ogbazghi *et al*., 2006). Germination rates in tapped stands in Eritrea are significantly lower (14 %–16 %) compared to those in untapped stands, where rates exceed 80 % (Ogbazghi, 2001). Excessive tapping leads to the production of seeds lacking viable embryos, significantly reducing seedling recruitment, and when this occurs during the wet season, the continuous resin flow hardens on the stems, thereby increasing the plant's susceptibility to fire hazards (Eshete *et al*., 2012; Rijkers *et al*., 2006). Over-tapped trees also exhibit reduced pollination rates, only 16 % compared to healthier specimens, and significantly lower fruit sets (Rijkers *et al*., 2006).

These trends underline the urgent need to revise current harvesting methods. Unsustainable tapping practices are a major factor in the ongoing decline of *Boswellia* species, and improvements in collection techniques are critical for the long-term survival of the trees. On a more positive note, germination trials under various temperature and moisture conditions indicate that germination itself is not a limiting factor for propagation. Studies confirm that *B. papyrifera* does not face significant dormancy issues (e.g. Rijkers *et al*., 2006; Ogbazghi *et al*., 2006; Lemenih & Teketay, 2003).

*Overgrazing*

Overgrazing or uncontrolled grazing significantly hinders the natural regeneration of *Boswellia papyrifera*. Livestock, particularly goats and cattle, prefer succulent seeds and seedlings. Studies show better seedling establishment in fenced areas compared to openly grazed sites. In Eritrea, seedlings reached only 15 cm in height and 1.5 cm in diameter after three years due to grazing pressure (Ogbazghi, 2001). The prolonged juvenile stage increases their risk of being eaten, trampled, or destroyed by fire and fuelwood collection (Eshete *et al*., 2012).

During the rainy season, herders defoliate *Boswellia* leaves for fodder, while in the dry season, livestock strip bark from the trees. Additionally, tapping creates wounds on trees that are further stressed by grazing. The plant's slow germination rate exacerbates its vulnerability, and grazed seedlings often lose all aboveground parts, leading to high mortality. In contrast, saplings show better survival, indicating that grazing affects younger stages more severely. Protection from grazing and other biotic disturbances has been shown to significantly increase seedling numbers in enclosed areas (e.g. CIFOR-ICRAF, 2011;

Tilahun, 1997; Dejene *et al.*, 2016). A classic example illustrating this principle comes from degraded rangelands and dryland forests, particularly in regions like the Horn of Africa (e.g., Ethiopia, Eritrea).

*Insect infestation*

Termites and wood-boring insects pose a serious threat to *Boswellia* species (Ogbazghi, 2001; Abdoul *et al*., 2012). Beetles and worms often burrow into live trees, especially those that are tapped. In Gondar, an unidentified worm caused more damage to tapped trees than to untapped ones (Eshete, 2011). Seed quality studies show insect damage to about 18 % of seeds in Ethiopia (Tilahun, 1997) and 20–25 % in Eritrea (Ogbazghi, 2001).

Trees weaken by insects, increase disease vulnerability, and contribute to adult mortality. Termites are also widespread and can worsen seedling. Combined, beetles and termites accelerate the decline of trees, especially as they dry out. Additionally, shallow roots make *B. papyrifera* highly susceptible to wind damage and uprooting. These threats, along with forest overuse and conversion, have caused major degradation. Effective rehabilitation and sustained management efforts must address these issues.

*Climate Change*

The *Boswellia papyrifera* tree's population and growth have declined due to climate change, primarily because of factors like increased drought conditions, decreased precipitation trends, high rainfall variability, and extreme temperatures in its already arid native habitats. The primary causes of the rapid reduction in *B. papyrifera* trees are human pressure and environmental degradation (Gidey *et al*., 2020; Lemenih *et al*., 2014), which can be worsened by climate change and increasingly frequent extreme climate events. These consequences also endanger the livelihoods of people who depend on frankincense production (Madera *et al.*, 2024), with some studies even predicting a possible half of frankincense production within the next 20 years (Tolera *et al*., 2013; Lemenih *et al*., 2014). In tropical woodland systems, *B. papyrifera* trees adapt differently to local climatic conditions; however, climate change may alter the leaf-bearing season, which could impact resin yield and crown carbon acquisition (Mengistu *et al*., 2012). The January–March tapping season in Ethiopia yielded the largest harvest of frankincense (Cherenet *et al.*, 2020; Eshete *et al.*, 2012). Therefore, by changing the tapping season, climate change specifically, variations in rainfall between and within years, as well as a change in seasonal rainfall, manifested as late or early beginning and cessation, climate change affects frankincense yield. The most prevalent drought conditions in recent years have been reported as a result of extremely low March-May rainfall in the majority of East African countries (IPCC, 2021; Taye & Dyer, 2024), and Eritrea and Ethiopia have been experiencing a notable increase in drought conditions (Measho *et al*., 2019; Mera, 2018; Mulualem *et al*., 2024). The climate change and other key threats to forest ecosystems and their impacts on *B. papyrifera's* regeneration and sustainability are summarized in Table 2.

**Table 2: Major Disturbances (Negative Factors) and their Impacts on *Boswellia papyrifera's* Regeneration and Sustainability**

| Factor | Description | Impacts |
|---|---|---|
| **Expansion of Farming** | Driven by resettlement, immigration, and demand for land to grow cash crops like cotton and sesame. | Loss of over 177,000 ha of forest; predicted a 90 % population decline in 50 years (Groenendijk *et al*., 2012; Gebrehiwot *et al*., 2002). |
| **Overexploitation and Extensive Tapping** | Unsustainable tapping methods (e.g., deep cuts, year-round harvesting) reduce seed viability and tree health. | Reduced seed viability and regeneration, fire risk increase, and lower fruit set (Rijkers *et al*., 2006; Eshete *et al*., 2012). |
| **Overgrazing** | Livestock damages seedlings and strips bark/leaves, especially in open-access areas. | Seedling mortality, stunted growth, and regeneration failure (Ogbazghi, 2001; Eshete *et al*., 2012). |
| **Insect Infestation** | Termites and wood-boring insects attack weakened or tapped trees. | Up to 25 % seed damage; tree mortality and forest degradation (Tilahun, 1997; Ogbazghi, 2001). |
| **Climate Change** | Drought, erratic rainfall, and extreme temperatures impact growth and resin yield. | Lower resin yield, pest spread, increased mortality, and habitat loss (Lemenih *et al*., 2014; Measho *et al*., 2019; IPCC, 2021). |

## Conservation and Restoration Measures for *Boswellia papyrifera*

The conservation and restoration of *Boswellia papyrifera*, shown in Fig. 2, require a multifaceted approach to address the various threats it faces. The conservation of *B. papyrifera* forests depends crucially on recognizing their ecological and socio-economic significance. Across various regions, *B. papyrifera* populations are dwindling due to interconnected challenges, notably the lack of seedling regeneration. Sustainable ecological restoration strategies prioritize woodland regeneration and sapling growth. These strategies also aim to enhance livelihoods through sustainable frankincense production.

Conservation strategies for *B. papyrifera* prioritize sustainable livelihoods and pest control while preserving genetic diversity, even in fragmented or degraded populations. Core and genetically distinct groups should be protected through in-situ and ex-situ methods, including enrichment planting and gene banks. Dryland areas that are vulnerable to climate change such as Afar and North Gonder require urgent focus. Trial plantations in varied environments can help conserve genetic traits and support future breeding. Immediate implementation of conservation and restoration efforts in Ethiopia and Eritrea is essential to sustain frankincense production and ensure the species' long-term survival.

### *Promoting Natural Regeneration and Seedling Survival*

Protecting *Boswellia papyrifera* regeneration requires grazing exclusion through fencing to prevent livestock damage and enhance seedling survival and growth. Effective fire management, including firebreaks and controlled burning, is crucial due to the fire's significant threat to woodlands and young trees. Artificial regeneration techniques, potentially drawing from local knowledge, should be explored to supplement limited natural regeneration. This may involve nurseries and planting, although past success has been limited, indicating a need for refined methods. These interventions aim to bolster the establishment and survival of new *B. papyrifera* individuals.

Area Closure to Facilitate Natural Regeneration

Protecting regenerated seedlings is crucial for restoring degraded forests. These forests require dual demands: ecological recovery and continued supply of tree products. Overgrazing severely damages seedlings by destroying their above-ground parts, making survival difficult. While area enclosures are known to encourage regeneration, other challenges must also be addressed. Restoration efforts should focus on establishing plantations and protecting enclosed areas, which help reduce soil degradation and shield young plants from fire, browsing, and trampling. Seedling mortality during dry seasons remains a major barrier to natural regeneration, but enclosures can improve survival rates and are vital for successful forest recovery.

While area enclosures are widely recognized for their significant potential to facilitate natural regeneration, their long-term effectiveness crucially depends on addressing persistent biotic disturbances. To truly foster successful regeneration, it is essential to ensure active protection within these enclosed areas, safeguarding young plants from recurring threats such as fire, browsing by livestock, and trampling. This continuous protection is fundamental for successful seedling establishment and the unimpeded growth of vegetation, thereby maximizing the ecological benefits derived from area closure itself.

Area exclosures, coupled with a brief tapping rest period (5–10 years), have proven more effective than continuously tapped, non-exclosed woodlands. Exclosures result in increased foliage, fruit, viable seed production, stable population structure, higher regeneration rates, greater frankincense yields, and reduced pest and fire damage (Gidey *et al*., 2020; Gebrehiwot *et al*., 2003; Rijkers *et al*., 2006; Tilahun *et al*., 2011; Eshete, 2011; Tolera *et al*., 2013; Lemenih *et al*., 2014; Abiyu *et al*., 2006). To support these efforts, diversifying livelihood sources within the woodlands is crucial. This includes harvesting non-timber forest products (NTFPs) such as grass, dead wood, honey, and medicinal plants, which have demonstrated success in dryland forest conservation elsewhere. These measures, combined with NTFP collection, are essential for sustainable *B. papyrifera* woodland conservation. Effective conservation requires the involvement of stakeholders with diverse interests, balancing ecological, economic, and biological criteria. Free grazing and unsustainable tapping practices pose significant threats.

Enrichment Planting to Support Natural Regeneration

Enrichment planting, alongside area closures, is essential to support the natural regeneration of *B. papyrifera*. However, this approach has received limited attention, and seedlings remain vulnerable to fire, trampling, and grazing. To enhance success, more silvicultural research is needed, particularly regarding seed collection, nursery duration, planting timing, and post-planting care (Gebrehiwot *et al.*, 2002). Although nurseries in Ethiopia are producing seedlings for enrichment planting, survival rates are low. For example, only 4.5 % of seedlings planted in 1999 and 8.7 % in 2000 survived in northern Ethiopia (Gebrehiwot *et al*., 2002), with similar outcomes reported in Eritrea (Gebrehiwot *et al*., 2002). A major reason for this is the lack of species-specific silvicultural knowledge. Despite limited success, the government of the two countries, NGOs, and private sectors have begun planting *Boswellia* in potential areas. To improve outcomes, enrichment planting and seed addition must be applied with proper techniques and timing. Additionally, preventing resin overexploitation is vital for maintaining high seed viability in natural forests, particularly in Eritrea and northern Ethiopia (Rijkers *et al*., 2006). Focused efforts on artificial regeneration are crucial for the long-term rehabilitation and conservation of *B. papyrifera* woodlands (Negussie *et al*., 2021)

*Proper Tapping Frequency and Tapping Intensity*

To protect *Boswellia papyrifera* trees and seedlings during incense harvesting, conventional tapping methods must be improved. Improper tapping harms adult trees by exposing them to pests, fire, and other threats (Eshete *et al*., 2012). While a total ban on tapping is unrealistic due to the species' socioeconomic value, stricter regulations and law enforcement are essential to reduce damage (Negussie *et al*., 2021). Sustainable harvesting also requires local community engagement and the development of strong institutions to establish long-term market connections that can motivate farmers to manage dry forests responsibly and preserve the ecological services of woodlands.

Intensive tapping negatively affects seed production. Adopting less harmful techniques, such as reducing the number of tapping points per tree, spacing out tapping frequency, and allowing rest periods, can help maintain seed viability (Rijkers *et al*., 2006). Overexploitation, especially in northern Ethiopia, must be curbed to preserve the species' regenerative capacity. Ultimately, adapting current practices and enforcing responsible management are vital for maintaining the health and biodiversity of *B. papyrifera* forests while supporting sustainable frankincense production.

*Policy and Governance*

Effective policy and robust governance frameworks are paramount for the sustainable conservation of *Boswellia papyrifera* forests. Current governance often presents notable gaps, particularly concerning specific policies for **sustainable harvesting quotas**, transparent **benefit-sharing mechanisms** with local communities, and stringent **enforcement of land-use zoning** to prevent agricultural encroachment into critical *Boswellia* habitats.

Crucially, the absence of comprehensive **management planning** and systematic **inventory and monitoring** is a major impediment. Policies must therefore be developed to mandate regular assessments of *Boswellia* population dynamics, regeneration rates, and the ecological impacts of harvesting. This data is vital for informed decision-making and adaptive management strategies.

Furthermore, effective policies are essential for shaping sustainable **frankincense value chains**. This includes establishing and enforcing specific **eco-certification standards** (e.g., fair trade, organic) to ensure equitable returns for harvesters and disincentivize unsustainable practices. Such policies, combined with the creation of **dedicated conservation funds** (potentially sourced from value chain profits or government allocation), can directly support field projects and empower local communities involved in *Boswellia* conservation.

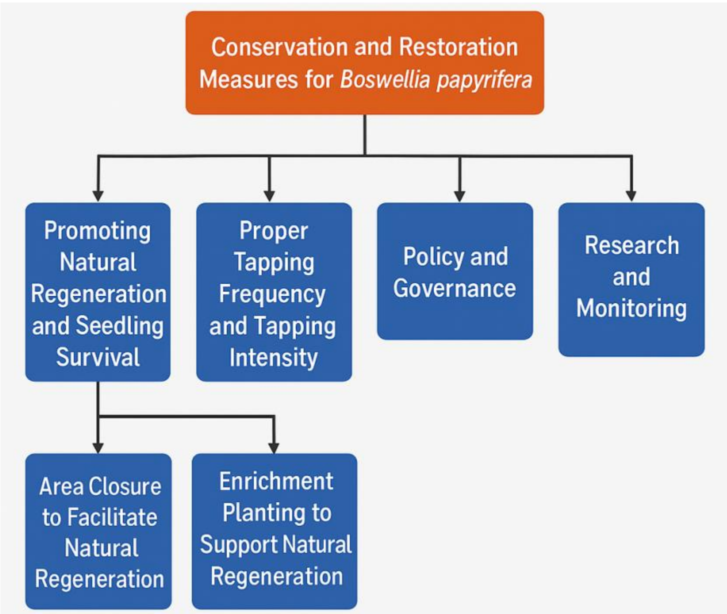
Addressing ambiguous **land ownership and tenure** issues through clear, legally binding policies is also fundamental, as secure tenure incentivizes long-term conservation investment by local populations. Beyond these specifics, broader national and regional **land-use planning policies** are critical to prevent further degradation. Promoting sustainable land management practices in areas adjacent to *Boswellia* woodlands, supported by appropriate policy incentives, will reduce pressure. Ultimately, long-term success hinges on involving relevant stakeholders, especially local communities, through participatory policy development and awareness programs that highlight the tree's multifaceted importance

(Gidey *et al*., 2020). These integrated policy efforts are indispensable for safeguarding *B. papyrifera* and its associated ecosystems.

*Research and Monitoring*

Effective conservation and restoration of *Boswellia papyrifera* woodlands critically depend on robust **research and sustained monitoring efforts**. Future initiatives must therefore prioritize comprehensive ecological assessments, specifically focusing on population dynamics, regeneration rates, and the diverse threats impacting these valuable species. Crucially, further research is indispensable to refine artificial regeneration techniques and to comprehensively understand the nuanced ecological requirements that underpin successful restoration (e.g., Ogbazghi, 2001). Moreover, dedicated studies are needed to precisely disentangle the complex, interacting drivers of tree degradation, such as the specific intensities of resin tapping, localized grazing pressures, and unsustainable lopping for cattle feed. The insights gleaned from such context-specific investigations are vital for formulating effective and targeted management policies. Ultimately, the long-term conservation of *B. papyrifera* and its associated ecosystems in regions of significant ecological and socio-economic importance, like Ethiopia and Eritrea, hinges on integrating these scientific findings into comprehensive, community-driven measures supported by robust and adaptive policies.

**Fig. 2: Conservation & Restoration of *Boswellia papyrifera* Trees in Ethiopia & Eritrea**



## DISCUSSIONS

The findings of this review underscore the precarious state of *Boswellia papyrifera* populations across Ethiopia and Eritrea, revealing a consistent pattern of decline driven by a confluence of interacting factors. The background information highlights the ecological adaptability of *B. papyrifera* to harsh dryland environments and its significant biological diversity within the *Boswellia* genus in the region. However, the geographical distribution data, coupled with the alarming population status characterized by a lack of regeneration, paints a clear picture of a species under considerable stress. The dominance of mature trees and the scarcity of seedlings and saplings, consistently reported across various studies (Eshete *et al*., 2005; Ogbazghi *et al*., 2006; Derero *et al*., 2018), indicate a trajectory toward local extinction if current trends persist.

The review synthesizes a wide range of threats, including agricultural encroachment, unsustainable tapping practices, and the detrimental impacts of overgrazing and insect infestation. Notably, the evidence suggests that excessive tapping not only reduces adult tree vigor but also significantly impairs seed viability and subsequent regeneration (Rijkers *et al*., 2006). Furthermore, the increasing influence of climate change, manifested through prolonged droughts and altered rainfall patterns, exacerbates these existing pressures, potentially impacting resin production and overall tree survival (Lemenih *et al*., 2014).

**Limitations of Existing Research:** While a substantial body of research exists on *B. papyrifera*, this review identified several limitations. Firstly, there is a notable variability in the methodologies employed across different studies assessing population status and regeneration rates, making direct comparisons challenging. Secondly, the long-term impacts of climate change on specific *B. papyrifera* populations and their adaptive capacity require more in-depth investigation. Thirdly, while the socioeconomic and cultural significance of the species is acknowledged, there is a relative paucity of research that quantitatively links conservation interventions with tangible benefits for local communities, which is crucial for ensuring long-term engagement and success. Finally, detailed silvicultural knowledge for effective artificial regeneration techniques remains limited, as evidenced by the low survival rates reported in enrichment planting initiatives (Gebrehiwot *et al*., 2002).

**Novelty and Unique Contribution:** This review offers a novel and timely contribution by consolidating a broad spectrum of research on *Boswellia papyrifera* in its core distribution range of Ethiopia and Eritrea. It provides an overarching understanding of the interconnectedness of various threats – anthropogenic and environmental – that are driving the species' decline. By explicitly highlighting the critical regeneration bottleneck and the limitations of current knowledge, this review underscores the urgency for a more integrated and adaptive management approach. It also emphasizes the potential for leveraging the cultural and religious significance of frankincense, particularly through the involvement of influential institutions like the Orthodox churches, as a unique avenue for promoting conservation.

**Future Research Directions:** Based on the identified gaps, several key research directions warrant further attention. Long-term ecological monitoring programs with standardized methodologies are crucial to accurately track population trends and the effectiveness of conservation interventions. Further research is needed to understand the specific physiological responses of *B. papyrifera* to different climate change scenarios and to identify climate-resilient genotypes. Investigating and optimizing silvicultural techniques for artificial regeneration, including seed provenance studies and post-planting care strategies, is essential. Moreover, future research should focus on developing and evaluating community-based conservation models that integrate sustainable harvesting practices with livelihood diversification strategies, ensuring local ownership and long-term success.

Finally, exploring the potential role of traditional ecological knowledge in informing conservation and restoration efforts could provide valuable insights.

## CONCLUSIONS AND RECOMMENDATIONS

The *Boswellia papyrifera* tree is undeniably crucial for the ecological and socioeconomic well-being of dryland regions, from a small community or local to national levels. However, this review unequivocally demonstrates that *B. papyrifera* populations in Eritrea and Ethiopia face severe threats, jeopardizing the species' long-term survival. The alarming rate of tree loss and vegetation degradation is driven by a combination of natural vulnerabilities and significant anthropogenic pressures, leading to rapid habitat disappearance. Therefore, for the benefit of the local and national communities, efforts should be made to conserve, restore, and sustainably produce *Boswellia* resources. In the regions of the two countries where *B. papyrifera* grows, silvicultural research on alternate propagation techniques, seed collection, nursery procedures, selecting suitable planting locations, and post-planting care should be enhanced. Enhancing harvesting techniques by lowering tapping intensity and permitting rest periods should be put into practice. Robust regulations and low enforcement measures should be implemented to lessen the harm that incense harvesting causes to trees and seedlings. Furthermore, to encourage natural regeneration, area enclosure techniques involving enrichment planting must be reinforced. Lastly, the restoration of Ethiopia's *Boswellia* woodland should start right away with the provision of management treatments for regenerated seedlings and the previously closed regions.

A particularly novel and potentially impactful recommendation is the central involvement of the Eritrean and Ethiopian Orthodox churches in leading both the conservation and restoration of *Boswellia papyrifera* trees and the sustainable production of frankincense. As the primary users of frankincense, the main product of *B. papyrifera*, these institutions possess significant cultural authority and a vested long-term interest in the species' survival. To leverage this, the two churches should proactively develop and submit conservation and restoration projects to governmental, non-governmental, and private aid organizations, as well as to **international environmental institutions, development banks, and global climate funds** for financial and technical support. Given the high economic and social benefits derived from *B. papyrifera*, the governments of both countries, alongside NGOs, should actively welcome and support these church-led initiatives, recognizing their potential for effective and culturally sensitive conservation outcomes. This unique partnership holds considerable promise for ensuring the long-term viability of *Boswellia papyrifera* and the preservation of the ecological and cultural heritage it represents.

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## CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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