The *Santalum album* is unique from seed to wood

The sandalwood tree is of great cultural, medicinal and commercial value. There are about 29 genera and 400 sandal species. The sandal tree is distinct in many ways, including tree phenology, hemiparasitic nature, seed structure and germination morphology, fragrant heartwood and oil of high economic value, resulting in illegal felling and threat to its existence. This correspondence emphasizes the uniqueness of the tree, which may be the basis for conducting future research on its botanical and eco-physiological characteristics.

Santalum album grows at a slow rate. It may start to flower at an early age of 2–3 years[1]. In the initial stages, the tree flowers once a year, but later it starts to flower twice a year, during March and September. The ripe fruits disperse from the mother tree during May and December[1]. The regular flowering of twice a year as observed in *S. album* is a rare phenomenon among tree species. In some species like mango and citrus, 'offseason' flowering is observed in certain locations due to environmental conditions or management strategies, but not as a natural phenology as observed in *S. album*.

The fruits of *S. album* are small (1.25 cm diameter), pulpy, globose drupe and purplish black in colour (Figure 1). Dicot plants normally produce seeds with well-formed seed coat and large cotyledons as storage tissue; however, sandal produces endospermous seed with a tiny cotyledon containing linear embryo and is devoid of seed coat (Figure 1).

Germination of sandal seed is a slow process requiring a minimum of 30 days for initiation[2]. Once imbibed, the tiny embryo elongates inside the seed prior to initiation of germination. Dileepa *et al.*[3] confirmed that the embryo inside *S. album* seeds grows up to 40% in size during imbibition prior to radicle emergence, establishing that the seeds are 'underdeveloped' during maturity and dispersal. The seeds demonstrate morphophysiological dormancy[4]. Contrary to the classification of Baskin and Baskin[5] which had stipulated that underdeveloped seeds would have an embryo : seed ratio (E : S) of <0.5, the E : S ratio in *S. album* was about 0.61 (ref. 3). Morphophysiological dormancy is a unique feature of tropical tree species, since most other species of this region like *Acacia* spp., *Albizia* spp., *Cassia* spp., etc. exhibit only physical dormancy.

Epigeal germination is a characteristic feature of cotyledonous seeds, whereas hypogeal germination is associated with most endospermous seeds. Sandal is a dicot plant with endospermous seeds; however, it exhibits epigeal germination. In a germinating seed of *S. album*, the radicle emerges and is anchored to the soil followed by elongation of the hypocotyl which forms a prominent arching[6] and eventually pulls the massive endosperm out of the soil (Figure 2 *a*), demonstrating epigeal germination. Subsequently, most of the food reserves from the endosperm are translocated to the lower portion of the seedling and the hypocotyl turns fleshy, and is referred to as 'carrot' of the seedling[7], which is yet again a unique phenomenon. A study conducted at the Forest College and Research Institute, Mettupalayam, Tamil Nadu, India showed that the massive endosperm of the sandal seed possesses a split stalk, which is another unique phenomenon. Once the endosperm is pulled out of the soil during germination, the split stalk elongates, and the rudimentary cotyledonary leaves pierce through the base of the split stalk and protrude out of the seed through the micropyle. It can be visualized alongside the split stalk of the endosperm, just before the straightening of the arch (Figure 2 *a*). Later, the cotyledon grows and give rise to a pair of leaves and forms the shoot system, whereas the endosperm with split stalk remains attached at the base of the seedling (Figure 2 *b*). Subsequently the split stalk gradually dries up and the endosperm drops while the split stalk remains attached to the young seedling (Figure 2 *d*). Further studies are required to throw more light on the seed structure and germination morphology of sandal seeds.

After germination, the seedling grows on its own only for a few months until it reaches about 6 inch height; later the young seedling dries and withers[8]. However, planting of 5–7-month-old seedlings in a container with a few seeds of *Casuarina equisetifolia* (or other legume species) could sustain seedling growth. This is because the sandal tree is an obligate hemiparasite. The tree continues to grow only if it can form a connection with the roots of other host plant species through 'haustoria' and extract nutrients such as phosphates and nitrates to enable its growth[9]. Annapurna *et al.*[10] reported that the roots of sandalwood can associate with more than 300 species of plants. Perhaps, nature has bestowed upon *S. album* the ability to associate with the surrounding vegetation and draw support from it so as to accomplish the unique task of producing fragrant wood enriched with oil.

Sandalwood is the second most expensive wood on earth[7]. It is the only wood that is sold in kilograms. The fragrant heartwood consists of close grains and is considered as one of the best-quality wood for handicrafts, much sought after for its fragrance and elegant look. The wood is resistant to termites and woodborers, and has high therapeutic value. The economic part of *S. album* is its heartwood, which is a 1–2 m log obtained from the bottom part of a mature tree. Mature sandalwood tree aged 25 years may weigh about 100 kg, of which the aromatic heartwood weighs about 20 kg. Sandalwood oil, known as the 'queen of essential oils', is obtained by steam distillation of heartwood which yields 5–7% of high-grade oil. The aromatic sandalwood oil exhibits a unique sweet and woody fragrance which is persistent for a long time (Figure 3). The international bulk price for sandalwood oil is more than Rs 200,000/kg, while in the retail domestic market it is sold at Rs 300,000/kg (ref. 11). Sandalwood is therefore known as a 'dollar-earning parasite'.

In a 1792 edict Tipu Sultan, the ruler of Mysore, declared *S. album* as a royal tree.

Figure 1. ***a***, Ripe fruits; ***b***, sandal seeds; ***c***, internal seed structure – ED, endosperm; EA, embryonic axis[3].

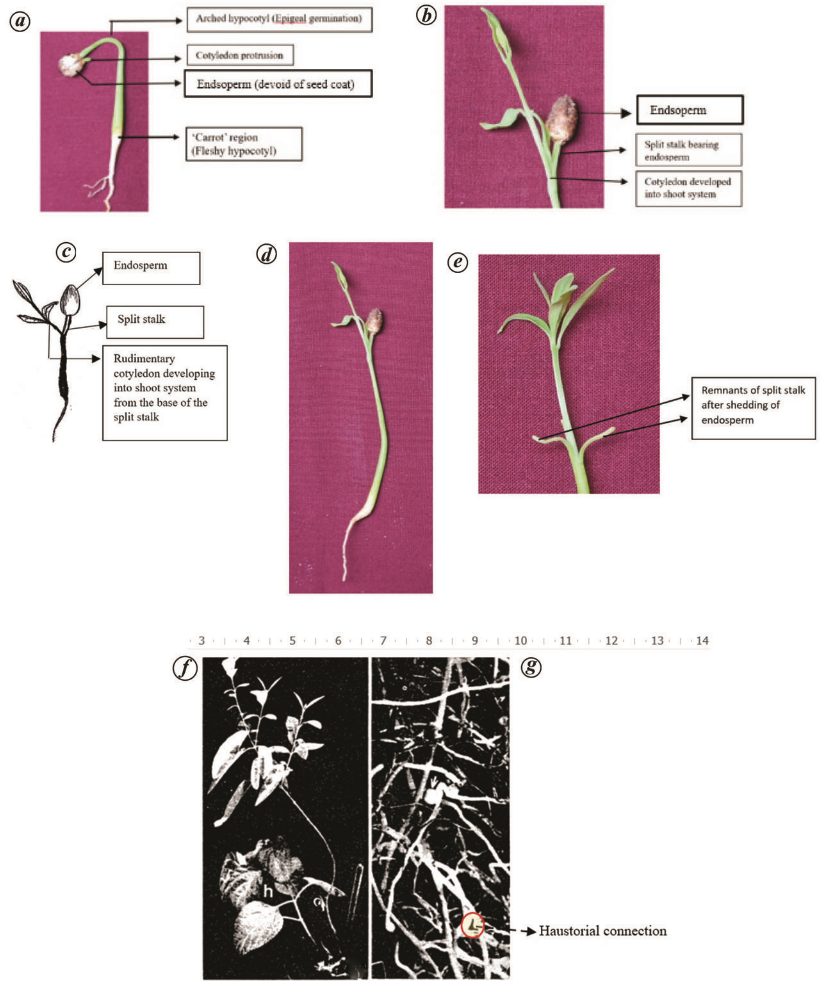
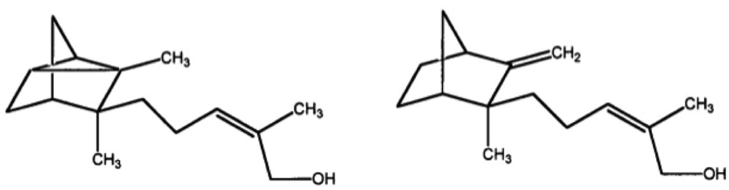


Figure 2. Morphology of seed germination of *Santalum album* seedling. ***a***, Stage 1: Arching of hypocotyl formed to pull out the endosperm from the soil. The cotyledon which develops into the shoot system emerges through the micropyle and is seen adjacent to the split stalk of the endosperm. ***b***, ***c***, Stage 2: Endosperm attached to the hypocotyl of the seedling through a 'split stalk', and the cotyledon which has emerged between the split stalk of the endosperm develops into a shoot system. ***d***, Juvenile seedling. ***e***, Stage 3: The endosperms shed from the seedling, but remnants of the split stalk remain attached to the seedling on both sides. ***f***, *Santalum* seedling along with a seedling of the host (h), *Lantana camara* one year after transplantation. ***g***, Portions of roots of seedlings shown in (***f***) revealing haustorial contact (arrow) between roots of the parasite and the host[6].



Alpha-santalol   Beta-santalol

Figure 3. Chemical constituents of sandalwood oil.

To protect the trees from illegal felling, the Governments of Karnataka and Tamil Nadu also adopted the 1792 edict[12]. However, the monopoly of sandalwood trade by the Governments of Karnataka, Tamil Nadu and Kerala has resulted in illegal felling and smuggling. Apart from mature trees, the young and immature trees are also felled, resulting in 90% loss of the natural population. Over exploitation has also decimated the tree population in other countries like Hawaii, Fiji, Indonesia and Malaysia. In 1997, the species was enlisted in the 'vulnerable' category of the IUCN Red List[7]. Although the ban on cultivation has been lifted, even today permission has to be obtained from the respective State Forest Departments to cut a sandal tree.

Thus, the sandalwood tree is unique in many aspects. Unlike majority of tropical trees, this tree flowers and disperses seeds twice a year. The seeds are devoid of seed coat. The dicot seed contains a large endosperm and a tiny embryonic axis with 'underdeveloped' plumule and radicle. The seeds exhibit morphophysiological dormancy. The endospermous seeds demonstrate epigeal germination. During germination, the rudimentary cotyledonary leaf emerges at the base of the split stalk of the endosperm and protrudes out of the seed through the micropyle, alongside the split stalk to form the shoot system. After few months of growth, the seedlings of *S. album* connect with host plants through the haustoria to suck essential nutrients, demonstrating their hemiparasitic nature of survival. The wood of the mature *S. album* trees is the second most valued timber on earth. The natural populations are being decimated due to uncontrolled illegal felling and smuggling. Therefore the species has been declared 'vulnerable' and enlisted in the IUCN Red List.

There is a need to undertake further botanical and eco-physiological studies on the sandal species to unravel their uniqueness with respect to correlation among tree phenology, seed development, seed structure and dormancy, germination morphology, hemiparasitic nature and development of unique wood characteristics.

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Potential of integrated approach of zinc fortification in maize

Attention towards the major nutrients than secondary and micronutrients is more for achieving the targeted yields. Zinc (Zn) nutrition plays a pivotal role in plant metabolism and yield potential of maize. Indiscriminate use of high-analysis straight fertilizers coupled with negligible or no application of organics has resulted in imbalanced soil nutrient status and micronutrients deficiency across the globe, and zinc in particular[1]. Zinc deficiency in human nutrition is widespread, after iron, vitamin A and iodine deficiencies. Nearly 49% of the global adult population does not get its daily recommended intake of 15 mg day^{-1} of zinc. This is one of the leading risk factors associated with diseases such as diarrhoea and retarded growth contributing to the death of about 800,000 people each year[2]. Negative correlation between irrigation and phosphorus was observed with Zn uptake which leads to the low Zn content in kernels, a major cause of Zn malnutrition among maize consumers[3].

Zinc enrichment in maize could be achieved using various agronomic strategies. Although application of inorganic sources alone is the common method adopted, integrated approaches (organics and inorganics) involving techniques like seed pelleting, solubilizing bacteria, enriched compost along with foliar spray at critical crop growth stages are cost-effective and sustainable options in the long run. It is also the way forward to enhance the availability of zinc from native soil reserves and to render better availability to the plants and translocation towards the sink.

A field experiment on zinc enrichment in maize was carried out at the College Farm, College of Agriculture, Professor Jayashankar Telangana State Agricultural University (PJTSAU), Rajendranagar, Hyderabad during *kharif* 2019. The geographical location of the experimental site is 17°19′19.2″N lat., 78°24′39.2″E long. and altitude of 542.3 m amsl. Agro-climatologically the area is classified as Southern Telangana Agro-Climatic Zone. The total rainfall received during the cropping period was 680.8 mm. The soil of the experimental site was sandy loam type, slightly acidic in pH (6.30), non-saline in electrical conductivity (EC) (0.21 dSm^{-1}), low in organic carbon (0.42%), low in available nitrogen (230.60 kg ha^{-1}), medium in available phosphorus (24.30 kg ha^{-1}), high in available potassium (388.40 kg ha^{-1}) and low in available Zn (0.54 ppm).

The experiment was laid out in randomized block design with ten treatments and replicated thrice (Table 1). Recommended dose of fertilizer (RDF) 200 : 60 : 50–N : P_2O_5 : K_2O kg ha^{-1}) N was applied in three equal splits (at sowing, knee-high and tasselling stage), total P was applied as basal and K was applied in two equal splits (at sowing and tasselling stage respectively). Farmyard manure (FYM) was enriched with zinc solubilizing bacteria (ZSB) @ 1 kg per 100 kg FYM for 22 days before sowing (T_2 and T_7 treatments). Seed pelleting was done by dissolving 3.6 g of $ZnSO_4$ in water. Polymer was added to above solution and made into a slurry by thorough stirring. The slurry was added to 1 kg seed in a polythene cover and thoroughly mixed for 4–5 min and shade-dried (T_4 and T_9). Enriched FYM was prepared by adding $ZnSO_4$ @ 50 kg ha^{-1} with 25 t FYM ha^{-1} 22 days before sowing (T_5 and T_{10}). Maize hybrid NK-6240 @ 20 kg ha^{-1} was sown adopting a spacing of 60 cm × 20 cm.