Sandalwood plantations – points to ponder

Doddabasawa^{1,*} and B. M. Chittapur²

¹Division of Farm Forestry, College of Agriculture, Bheemarayanagudi, Yadgir 585 287, India

²Directorate of Extension, University of Agricultural Sciences, Raichur 584 104, India

East Indian sandalwood (*Santalum album* L.) is one of the precious woods known for sweet fragrant aroma and commercial value in both national and international markets. Besides, its wide adaptability to varied climate, hosts and edaphic conditions have attracted farmers and corporates for commercial venture. Sandalwood being a hemi-root parasite, the successful establishment of sandalwood plantation depends on the understanding of parasitism ecology, especially the relations between host and parasite, their ratio and other silviculture techniques. Hence, the present article aims to understand these issues for commercial upscaling. Sandalwood relies largely on host plants for mineral nutrients and water through haustorial connections which act as a physiological and physical bridge between the parasite and the host. It parasitizes over a vast array of plants from grasses to trees, whereas leguminous associations are superior. Deep-rooted and slow-growing perennial hosts help in sustained growth. For better yield of heartwood and oil sandalwood should be grown over 15 years, whereas optimum rotation age would be 25–30 years. Sandalwood can be planted either through direct dibbling of seeds near the hosts in the same pit or adjacent to the hosts. Better establishment occurs when sandalwood is grown with potted host followed by secondary hosts in the field. Association of sandalwood and host would be strong when the distance is around 2.5–3 m with host to parasitic ratio of 2 : 1 or 3 : 1. However, questions on parasitism ecology still remain.

Keywords: Ecology, haustoria, hosts, parasite, sandalwood.

In recent times farmers are showing great interest in growing a few economically important tree species in the form of plantations and as integral component of agro-forestry systems. Sandalwood is one such species which is gaining wider attention among farming and corporate communities for its high economic value. India is the major exporter of East Indian sandalwood in the world, accounting for 90% of the total global production. Most of the produce comes mainly from natural stands, wherein presently sandalwood trees are under tremendous pressure due to indiscriminate exploitation, especially for high export value of wood¹ coupled with poor regeneration, fire, disease and change in land-use pattern^{2–4}.

Consequently, the production has reduced from 400 to 500 Mg (mega gram) year⁻¹, whereas the global demand is between 5000 and 6000 Mg year⁻¹ (ref. 5). The declining natural stock has increased the price of sandalwood in the national and international market by many folds^{2,6,7}, and East Indian sandalwood continues to enjoy the prime position attracting greater commercial venture⁸.

However, regeneration and establishment of sandalwood plantations were mostly unsuccessful because of poor understanding of parasitism ecology, i.e. sandalwood–host relationship⁹. Being a hemi-root parasite, it has unique and complex silvicultural characteristics¹⁰. Further, lack of precise information on cultivation practices is a hindrance in the successful establishment of sandalwood. Here we review the available information to suggest the best possible establishment techniques.

About sandalwood

Genus *Santalum* belongs to the family Santalaceae consisting of 16 species and their variants most of which are geographically and reproductively isolated^{11,12}. These are known for their fragrant heartwood and oil. Most sandal species are small trees or large shrubs with erect or dropping branches. All the sandal species are slow-growing and root parasites. A few sandal species are commercially important in terms of quality and quantity of aromatic oil. Among these, *Santalum album* L. considered the queen of sandal species having higher concentration (6–7%) and good quality oil with sweet, fragrant and persistent aroma is used in perfumes, cosmetics and medicine^{1,13}. Further, the soft wood is also used in carvings and intricate designs. The natural distribution of sandalwood extends from 30°N to 40°S, that is, from Indonesia in the east to Juan Fernandez Islands (Chile) in the west and from Hawaiian Archipelago in the north to New Zealand in the south. Wide distribution occurs in India with highly concentrated population in the peninsular region, mainly in Karnataka, Tamil Nadu and Kerala^{11,14}.

It is a small to medium-sized evergreen tree species that prefers shade in the early stages, while in the later stages the plant requires abundant sunlight for luxuriant growth. Initial growth is slow and the plant attains a height of 12–15 m and girth of 1–2.4 m (ref. 15). Sandal grows well under varied climatic conditions up to an altitude 1800 m, prefers warm to monsoon climate (500–3000 mm rainfall), and flourishes well under dry

*For correspondence. (e-mail: dkpatil2020@gmail.com)

monsoon climate receiving 600–1600 mm rainfall. It adapts as well to cool climate and long dry periods and grows well on a wide variety of soils comprising sandy, clay, red and lateritic loamy and even black cotton soils. However, well-drained light to medium soils are preferred. Whereas, it does not tolerate waterlogged soils and cool climatic conditions^{16,17}. Its wide adaptability, non-specific parasitization (parasitizes more than 300 plant species), and high economic value are attracting the farming community for commercial production.

Parasitism

Sandalwood is a hemi-root parasitic tree and relies largely on host plants for mineral nutrients and water. The hemi-parasitic nature was first detected by Scott in 1981 and later confirmed by Barber^{18,19}, who studied the root system of sandalwood in detail and reported haustorial formation on the rootlets. The formation of haustoria is more or less confined to younger roots; the main roots probably play little part in the absorption of nutrients (Figure 1). In the absence of a host, the haustorium remains small and ultimately withers away, but if a rootlet of a suitable host is present, it grows rapidly assuming the shape of a flattened bell. Sandal root and the host develop direct vascular connections, which later undergo secondary growth^{20,21}. The vascular connection between the host and sandal becomes so intimate that the host root and parasite root become almost a single physiological unit, a physical and physiological bridge (Figure 2)²². Further, hosts are not only important for fulfilment of nutrient and water needs, but also provide shade in the early stages of sandal growth when necessary^{23,24}. Some reports suggest the dependence of sandal on hosts for Ca, Fe (ref. 25), N, P (ref. 26), K, and Mg (refs 27, 28), whereas others include amino acids, proline, malic acid and sugars for the synthesis of carbohydrates^{13,29}.

Sandal requires a host for survival from seedling to maturity^{13,30–32}, though in the early stages it derives its nutritional requirements from the seed reserve and soil³³. It can survive up to 1 year without a host. Nagaveni and Srimathi^{34,35} observed poor survival of sandal without host after the second and third years, necessitating the presence of host plants in later stages³⁶. Ehrhart and Fox³¹ identified host requirement at three different stages for successful establishment, one at the seedling stage (the primary host/pot host) involving planting of host plants in containers having sandalwood seedlings during nursery propagation; second at intermediate between nursery and field, and third stage as long-term host in the field throughout the life of the sandal tree (secondary host). However, in practice hosts are being largely used at two stages, viz. as primary hosts in seedling stage for a short period (6 months to 2 years) and secondary hosts in the field as long-term hosts. The parasitic nature of sandal

and beneficial influence of host plants on the growth of sandal are widely studied^{13,30,37–39}. However, what exactly sandal draws from its hosts is still unclear.

Host

Host selection is an important factor for the successful establishment of sandal plantations¹³. Sandal is known to parasitize a large number of plants from grasses to trees. In some instances, it was found to resort to self-parasitism⁴⁰.

Figure 1. Rooting pattern of sandalwood.

Figure 2. Physiological and physical bridge between sandalwood and host through haustorial connection (left-hand side sandalwood root and right-hand side host root).

Further, differential growth responses of sandal were observed with different hosts⁴¹. Pot-culture studies helped identify good, moderately good and poor host species based on the number of haustoria produced, and interaction of parasitism on growth and performance of sandal and its host on the basis of survival, growth, vigour and mortality rate of both sandal and host^{42–45}. Usually with suitable hosts the sandal trees have thick canopy, wider and darker green leaves, in contrast to small and yellow chlorotic leaves with unsuitable hosts⁴⁶.

The size and shape of the haustorial formation depend on the type of host attachment⁴⁷. Better growth of sandalwood was observed with leguminous host species such as *Acacia*, *Sesbania*, etc.^{30,48} (Table 1), probably due to higher availability of nitrogen which might increase the number and size of haustorial formation^{30,49}. Leguminous species also have thin roots with watery skin root which helps in easy penetration and formation of haustorial connection. *Acacia* was the most preferred host under natural condition^{30,50,51}. However, it is better to have multiple compatible hosts consisting of both leguminous and non-leguminous species. Multiple hosts are expected to reduce the parasitic load, as in most instances the establishment of sandal plantations with one or two individuals of the same host species has resulted in the decline or death of hosts as well as sandalwood after 5–10 years due to parasitic load⁵². Inclusion of multiple species ensures long-term survival of sandal and hosts. Further, presence of multispecies increases the seasonal source of water and nutrients¹⁰. Barrett *et al.*⁵³ attributed variations in the distribution of nutrient within the shoots and leaves of *Santalum spicatum* to contribution from diverse host species. The differential requirement of water and nutrients by different host species could be another reason for the potential survival of sandalwood.

Preferred perennials

The formation of heartwood is influenced by the host on which sandal is parasitized, the edaphic and climatic factors as well as age. Basically, sandal is a slow-growing species, displaying an increment of 1 cm girth year⁻¹ under natural conditions, however, under favourable conditions, increment in girth extends to 5–6 cm year⁻¹ (refs 17, 54). Normally, heartwood initiation begins around 10–13 years in India⁴⁰, whereas economical rotation age is between 30 and 60 years⁵⁵. Further, the concentration and composition of oil also varies with maturity. For instance, young trees of 10 years having >16 cm diameter are found to have 0.2–2.5% of oil and 60–85% santalols, whereas mature trees that are 30–50 years old with <32 cm diameter have 2.8–5.6% oil and 90% santalols⁵⁶. Therefore, the most economical rotation age of sandal would be around 30 years or more, to obtain higher quantity and quality of heartwood and oil⁵⁵. There are

instances where it is advised to harvest at the age of 15 years for financial reasons^{57,58}. However, there is little published information on the productivity of heartwood at this age⁵⁹. Jonathan *et al.*⁵⁹ reported average heartwood and oil concentration per tree of 5.8 and 0.28 kg respectively, 16-year-old Indian sandalwood planted with a density of 260 trees ha⁻¹ in Kununurra, Western Australia, which was half the expected yield at this age. Therefore, they suggested enhancing the rotation period for maximization of yield. A few other studies also suggested a rotation period exceeding 15 years¹³.

The appropriate economical rotation age of sandalwood would be between 25 and 30 years with perennial host species having rotation period of over 30 years. Some studies have also indicated a few short- and medium-rotation tree species such as *Casuarina equisetifolia*, *Acacia mangium*, etc. to be good hosts for sandal but harvested between 8 and 12 years and, therefore, should not be selected as long-term hosts. In general, perennial species are to be preferred over annuals and/or short rotation species to sustain sandal for longer periods^{60–63}.

Rooting pattern in hosts

It is evident that sandalwood depends on hosts for mineral nutrients and water^{64–67}. Rocha *et al.*⁶⁸ observed higher pre-dawn water potential (–0.85 MPa) in sandalwood with host than without host (–1.27 MPa). They observed reduction in water potential after removal of host which resulted in wilting and leaf-shedding of sandal, thus affecting growth and productivity. Therefore, host plants are necessary to maintain better water potential in sandalwood. Shallow-rooted annuals and perennial hosts may not be good as they are unable to supply water to support sandal during the dry period. Preference, therefore, should be given to deep-rooted hosts which access water from deeper layers during drought⁶⁹.

Preferred economic hosts

Long gestation period of sandalwood has resulted in the inclusion of some economically important horticultural species which help get interim returns^{70,71}. Viswanath *et al.*⁷² observed better growth of sandal with mango (*Mangifera indica*) under intensively managed plantations, followed by amla (*Phyllanthus emblica*). Singh *et al.*⁷³ found greater height, collar diameter, crown size, clear bole and survival of sandal with *Citrus aurantium* compared to *Casuarina equisetifolia* and *Panicum granatum*. Nevertheless, too little information is available to draw any generalization on suitability of species for a particular agro-climatic region. However, inclusion of suitable multiple host species of commercial importance comprising N₂-fixing and non-fixing tree species needs consideration for a viable system. Parasitism can suppress the biomass and photosynthesis of the associated host

Table 1. Suitable and unsuitable hosts of *Santalum album* L. (adapted from Teixeira da Silva *et al.*⁸⁰)

Region	Suitable hosts	Family	Unsuitable hosts	Family	Reference
India	<i>Azadirachta indica</i> A. Juss.	Meliaceae	<i>Butea monosperma</i> (Lam.) Taub.	Fabaceae	88
	<i>Cassia fistula</i>	Fabaceae	<i>Dodonea viscosa</i> Jacq.	Sapindaceae	
	<i>Cassia siamea</i> (Lam) Irwin et Barneby	Fabaceae	<i>Gmelina arborea</i> Roxb.	Lamiaceae	
	<i>Dalbergia latifolia</i> Roxb.	Fabaceae	<i>Melia azedarach</i> L.	Meliaceae	
	<i>Ficus benghalensis</i> L.	Moraceae	<i>Tamarindus indica</i> L.	Fabaceae	
	<i>Grevillea robusta</i> A. Cunn. ex. R.Br.	Proteaceae			
	<i>Pithecellobium dulce</i> (Roxb.) Benth	Fabaceae			
	<i>Pongamia pinnata</i> (L.) Panigrahi	Fabaceae			
	<i>Syzygium cumini</i> (L.) Skeels.	Myrtaceae			
	<i>Wrightia tinctoria</i> (Roxb.) R.Br.	Apocynaceae			
	<i>Zizyphus mauritiana</i> Lam.	Rhamnaceae			
	<i>Acacia nilotica</i> (L.)	Fabaceae	Not recorded		
	<i>Bauhinia biloba</i> L.	Fabaceae			
	<i>Cassia siamea</i> (Lam) Irwin et Barneby	Fabaceae			
Australia	<i>Casuarina equisetifolia</i> L.	Casuarinaceae			13, 30
	<i>Dalbergia sissoo</i> Roxb.	Fabaceae			
	<i>Melia dubia</i> Cav.	Meliaceae			
	<i>Pongamia pinnata</i> (L.) Panigrahi	Fabaceae			
	<i>Terminalia arjuna</i> (Roxb.) Wight & Arn.	Combretaceae			
	<i>Terminalia alata</i> Heyne ex. Roth.	Combretaceae			
	<i>Wrightia tinctoria</i> (Roxb.) R.Br.	Apocynaceae			
	<i>Acacia trachycarpa</i> E. Pritzal	Mimosaceae	<i>Eucalyptus camaldulensis</i> Dehnh.	Myrtaceae	
	<i>Acacia ampliceps</i> Maslin.	Mimosaceae			
	<i>Sesbania formosa</i> (F. Muell) N. Burb.	Papilionaceae			
	<i>Azadirachta indica</i> A. Juss.	Meliaceae	<i>Artocarpus integrifolia</i> L.	Moraceae	
	<i>Cajanus cajan</i> (L.) Millsp.	Papilionaceae	<i>Acacia curculiformis</i> A. Cunn. Ex. Benth.	Fabaceae	
	<i>Casuarina equisetifolia</i> L.	Casuarinaceae	<i>Swietenia mahagani</i> L.	Meliaceae	
	<i>Eucalyptus camaldulensis</i> Dehnh.	Myrtaceae			
China	<i>Pongamia pinnata</i> (L.) Panigrahi	Fabaceae			41
	<i>Tectona grandis</i> L.	Lamiaceae			
	<i>Wrightia tinctoria</i> (Roxb.) R.Br.	Apocynaceae			
	<i>Acacia curculiformis</i> A. Cunn. Ex. Benth.	Fabaceae	<i>Artocarpus heterophyllus</i> (Wall.) R. N. Park.	Moraceae	
	<i>Acacia confuse</i> Merr.	Fabaceae	<i>Camellia odorata</i> Abel.	Theaceae	
	<i>Albizia lebbek</i> (L.) Benth.	Fabaceae	<i>Mangifera indica</i> Linn.	Anacardiaceae	
	<i>Cesalpinia pulcherrima</i> L.	Cesalpiniaceae	<i>Ormosia fordiana</i> Oliv.	Papilionaceae	
	<i>Casuarina junghuhniana</i> L.	Casuarinaceae	<i>Pterocarpus echinatus</i> Pers.	Fabaceae	
	<i>Cajanus cajan</i> (L.) Millsp.	Papilionaceae	<i>Syzygium cumini</i> (L.) Skeels.	Myrtaceae	
	<i>Kuhniarosa marnifolia</i> Vent.	Asteraceae	Not recorded		
	<i>Lantana camara</i> L.	Lamiaceae			
	<i>Gardenia jasminoides</i> Ellis.	Rubiaceae			
	<i>Hibiscus rosasinensis</i> L.	Malvaceae			
	<i>Phyllanthus reticulatus</i> Poir.	Euphorbiaceae			

(Contd)

Table 1. (Contd)

Region	Suitable hosts	Family	Unsuitable hosts	Family	Reference
China	<i>Acacia confuse</i> Merr. <i>Dalberg iaodorifera</i> T. Chen. <i>Kuhniaros amarnifolia</i> Vent. <i>Acacia confuse</i> Merr.	Fabaceae Fabaceae Asteraceae Fabaceae	<i>Bischofia polycarpa</i> (H. Levl.) Airy. Shaw <i>Dracontomelon duperreanum</i> Pierre	Euphorbiaceae Anacardiaceae	90–92 93, 94
	<i>Calliandra haematocephala</i> Hask <i>Caesalpinia sappan</i> L. <i>Erythrina corallodendron</i> L.	Mimosaceae Fabaceae Papilionaceae	<i>Bauhinia blakeana</i> Dunn. <i>Delonex regia</i> (Hook.) Raf. <i>Leucaena leucocephala</i> Lam. <i>Ormosia pinnata</i> (Lour.) Merr.	Leguminosae Leguminosae Mimosaceae Papilionaceae	
India	<i>Casuarina equisetifolia</i> L. <i>Dalbergia sissoo</i> Roxb.	Casuarinaceae Fabaceae	Not recorded <i>Aquilaria sinensis</i> (Lour.) Gilg.	Thymelaeaceae	21, 68 95
China	<i>Lonicera japonica</i> Thunb.	Caprifoliaceae			
India	<i>Acacia nilotica</i> L. (Delile) <i>Cassia siamea</i> (Lam) Irwin et Barneby	Leguminosae Leguminosae	<i>Prosopis juliflora</i> (Sw) DC <i>Azadirachta indica</i> A. Juss. <i>Leucaena leucocephala</i> Lam. <i>Albizia lebbbeck</i> (L.) Benth. <i>Tectona grandis</i> L. <i>Inga dulce</i> (Roxb.) Benth <i>Cocos nucifera</i>	Leguminosae Meliaceae Leguminosae Leguminosae Lamiaceae Fabaceae Arecaceae	79

Table 2. Characteristics of host plants parasitized by sandalwood under natural population in semiarid tropics⁷⁹

Host species	Characteristics			Water-use efficiency of trees (kg/cm)
	Family	Effective formulation of nodulation	Phenotypic features	
<i>Acacia nilotica</i>	Leguminosae	Present (specificity to <i>Rhizobium</i>)	Extensive lateral roots, sparse crown, slow-growing nature	45.00*
<i>Prosopis juliflora</i>	Leguminosae	Present (specificity to <i>Rhizobium</i>)	Exotic and fast-growing, sparse crown	37.60*
<i>Azadirachita indica</i>	Meliaceae	Absent	Dense crown, slow-growing	13.70*
<i>Tectona grandis</i>	Lamiaceae	Absent	Deciduous, fast-growing, sparse crown and high water requirement	Not found
<i>Cocos nucifera</i>	Aracaceae	Absent	Sparse crown, extensive lateral root system	Not found
<i>Albizia lebbbeck</i>	Leguminosae	Present (non-specific to <i>Rhizobium</i>)	Fast-growing, smaller number of nodules and non-translocation of nitrogen to dry matter	Not found
<i>Leucaena leucocephala</i>	Leguminosae	Present (specificity to <i>Rhizobium</i>)	Exotic and extensive growth, and prolific regeneration	Not found
<i>Pithecellobium dulce</i>	Leguminosae	Present (specificity to <i>Rhizobium</i>)	Exacting species, sparse crown	11.9*
<i>Cassia siamea</i>	Leguminosae	Absent	Extensive lateral roots and moderate crown	21.5*

*Water-use efficiency was obtained from Tomar *et al.*⁷⁷ on the performance of 31 tree species and soil condition in plantations established with saline irrigation (Doddabasawa *et al.*⁷⁹).

species^{63,74,75}. Some studies have documented the decrease in productivity and/or reproductive potential of hosts and even population dynamics of hosts in both root and shoot parasites⁷⁶.

Reverse translocation

Studies have revealed an increase in mineral and nutrient contents in some host plants due to reverse translocations, especially of P, Ca and Mg, which in turn affects the growth and development of sandal⁷⁷. For instance, Rocha *et al.*²¹ reported 26% and 35% reverse translocation of P from sandal tree to host with *Casuarina* and teak respectively.

Growth rate of host species

Sandal is a shade-demander in the early stages and later it needs abundant sunlight for photosynthesis. Therefore, fast-growing host species should not be selected as they are likely to overtop sandal plants. For instance, Barbour⁷⁸ observed suppressed growth of sandal with *Khaya senegalensis* (African mahogany) due to its rapid growth and large canopy which reduced the availability of sunlight. Similarly, Doddabasawa *et al.*⁷⁹ reported suppression of sandal growth with the fast-growing and exacting species *Leucaena leucocephala* and *Prosopis juliflora*. Slow growing species (*Acacia*) seem ideal as they have sparse canopy and are thorny in nature. Besides providing shade in the early stages, they also protect sandal plants from browsing animals²³.

Leguminous plants have an edge over others due to greater availability of nutrients, especially nitrogen and amino acids. Teixeira da Silva *et al.*⁸⁰ reported association of sandal with Fabaceae, Mimosaceae, Papilionaceae, Casuarinaceae, Meliaceae, Myrtaceae, Apocynaceae, Lamiaceae and Rhamnaceae, the association with Fabaceae being predominant. Further, not all species of these families were good hosts, and even with the leguminous family species such as *Tamarindus indica*, *Butea monosperma*, *Delonix regia*, *Bauhinia blakeana* and *Cassia surattensis* were found to be poor hosts (Table 1). Similarly in Australia, Barbour⁷⁸ observed better growth of sandal with leguminous hosts, but not with all leguminous species. In the Indian subcontinent, Doddabasawa *et al.*⁷⁹ suggested *Acacia nilotica* and *Cassia siamea* as the most suitable long-term hosts. The non-suitability of hosts largely depends on the characteristics of host species (Table 2).

Plantation establishment

Direct sowing of sandalwood seeds

This method is practised in southwestern Australia, where sandal seeds are sown directly with planted hosts in

the field. *Acacia acuminatum* is planted in the first year followed by sandal in the second and third years. Four untreated seeds of *S. spicatum* are sown around the host as close as practicable at 1 m distance with a depth of 5 cm (ref. 81). This technique reduces the cost of cultivation and period of establishment in the field. Secondly, the roots of young sandal seedlings are brittle and so is the haustorial connection formed with the potted hosts, and hence liable for damage even under careful handling during transplantation. However, in the dibbling method survival percentage of sandal as well as host is very low. Alternatively, Woodall and Robinson¹⁰ found three times (70%) more successful establishment while sowing pre-germinated sandal seeds with host on the same day compared to the former method.

Seedlings without primary host

Seedlings raised in containers (sandal relies largely on seed reserves/endosperm in the initial stage for a period of 6 months to 1 year) are planted with host either in the same pit or adjacent to the pit. Planting sandal in the same pit along with host at distance of 20–30 cm is good. Higher growth rate of host may affect the growth of sandal or vice versa. Initially, it may be good for sandal as it needs shade, but at later stages the host needs to be pruned frequently to enhance the availability of sunlight for sandal. However, frequent pruning may reduce the growth of the host and in turn the accessibility of resources from the host to sandalwood. Further, formation of haustoria on lateral roots of parasites is not only for physiological access but also for physical support. In this context, sandal grown on the same pit may be susceptible to wind. Besides, planting of sandal seedlings without primary host adjacent to the secondary host in the field also results in low success rate and growth of sandal due to poor association with the host and/or it takes longer time for formation of the haustorial attachment with the adjoining hosts. Survival rate and performance of sandal improve when seedlings raised with the primary host in a pot/container are planted adjoining to the secondary host⁸².

Seedlings with primary host

The sandalwood seedlings initiate haustoria within 30 days after germination with the associated host species³⁵. Sandal needs presence of hosts at three different stages; one at seedling stage (primary host/pot host) involves planting of host plants in containers having sandal seedlings during nursery propagation; second at intermediate between nursery and field, and third stage as long-term host in the field throughout the life of the sandal tree (secondary host)³¹. However, in practice, hosts are being largely used at two stages as primary hosts in seedling

Table 3. Spacing geometry and host-to-parasite ratio in commercial *Santalum album* in India

Spacing adopted	Details	Host-to-parasite ratio	Population	Reference
5 m × 4 m	5 m distance between rows and 4 m distance within a row (between two sandalwood plants one rosewood or teak or eucalyptus was planted) rendering effective distance between trees within rows in to 2 m	1 : 1	500 trees of sandal ha ⁻¹ and 500 trees of host	96
6 m × 3 m	With amla at the same spacing between sandal in the quincuncial method (distance from host is 3 m)	1 : 1	555 trees of sandal ha ⁻¹ and 555 trees of amla ha ⁻¹ (total density 1110)	58
4 m × 4 m	With casuarina at the same spacing between sandal in the quincuncial method (distance from host is 4 m)	1 : 1	555 trees of sandal ha ⁻¹ and 555 trees of amla ha ⁻¹ (total density 1110)	58
4 m × 5 m	4 m distance between the rows and 5 m distance between plants within a row; sandalwood was planted at a distance of 2.5 m from the host	1 : 1	500 trees of sandal ha ⁻¹ and 500 trees of host	70

Figure 3. Sandalwood rooting pattern indicating horizontal growth through lateral roots.

stage for a short period of 6 months to 2 years, and secondary hosts in the field as long-term hosts comprising perennial trees. Suitable hosts in the pot and field greatly increase the rate of successful establishment and growth of sandal^{13,31,37}.

Spacing and planting density

Cultivation of sandal is rather complex as it involves both host and parasite, and accommodating them together is rather tricky. Sandalwood can generally extend its lateral roots in the surrounding areas up to 1.5–3 m for establish-

ing association with the host. This extension also helps as a physical anchorage to the sandal plant (Figure 3). Ananthapadmanabha⁷⁷ reported that sandal cannot be grown beyond 2.2 m from the host plant; otherwise the growth of sandal is significantly hampered. Davit⁸³ observed that the attraction of root parasite to the host was limited beyond 3 m. The optimum spacing would be 1.5–3.0 m (Table 3). In the absence of hosts, sandal was found to parasitize its own root suckers for survival^{33,84,85}.

In most instances, the ratio of host to parasite is 1 : 1 (Table 3). This ratio is critical for survival and productivity of sandal trees as well as the host plants. Equal host-to-parasite ratio (1 : 1) heavily leaning towards parasite leads to heavy parasitic load, and hence may cause death or decline of the host population, decreasing the ratio further. Therefore, host and sandalwood ratio of 2 : 1 and 3 : 1 needs consideration⁸⁶. At present, a spacing of 5 m × 5 m for the hosts with a sandal plant at the middle of four host plants with host-to-parasite ratio of 4 : 1 is being practised. Further, it is suggested to have hosts of multiple species comprising both leguminous and non-leguminous commercially important trees, with sandal being the subsidiary crop^{21,87}.

Conclusion

Of late the interest in sandal, especially in *S. album* is growing and many commercial plantations are coming up on private lands for its commercial value. Sandal being a hemi-root parasite, interactions between host and sandal are complex and vary with the host and agro-climatic situation. Therefore, we need thorough in-depth knowledge for commercial success. Much of the available information particularly on hosts is from pot-culture studies, and upscaling of these results to the field level is rather difficult to comprehend with regard to economical rotation age, selection of hosts, spacing and host-to-parasite ratio. However, it is suggested to have multiple hosts of commercial importance comprising both perennial leguminous and non-leguminous tree species. Hosts having

deep root system and slow-growing nature like genus *Acacia* in 4:1 host-to-parasite ratio, with hosts spaced at 5 m × 5 m and sandal between the four host plants with need-based tending operation.

Future line of work

Sandal cultivation is a promising venture and with liberalization from governments, commercial production is spreading across the agrarian landscape, however, the production potential is yet unknown and uncertain. Presently, sandal is found to survive with a vast array of plants, especially short-rotation species like *Casuarina* and in some instances even with fruit trees like citrus, amla, mango and other economical horticultural and forestry species. As a parasite sandal inhibits the associated host, but the economical equilibrium between host and sandalwood is not yet to be ascertained. Perennial trees of long rotational period of 25–30 years would appear beneficial, but there are no long-term studies to confirm this. Being a combination of host and parasite plants, the association is complex and warrants a thorough research back-up with regard to nursery management, early establishment, host–parasite interface, number and type of host/s, their ratio, economic rotation age, watering, fertilization, chemical needs, pest control (if any, in both host and sandalwood), etc. Further, the parasite also has an impact on productivity of the associated economical species. In all, there is a long way to go before appreciation and recommendation of any system for commercial production of sandal.

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