of ANOVA and MATLAB by which plant performance could be improved.

- The results show that by changing one input variable, i.e. roller speed, and keeping temperature and feed rate as constant for both double-electrode as well as single-electrode HTS methods, maximum yield % to recover ilmenite using the former method (R^2 = 69.27%) is better than the better method (R^2 = 67.39%).
- Grade % using double-electrode HTS method (R^2 = 99.68%) is better than single-electrode HTS method (R^2 = 97.42%). Mainly, recovery % using the former method (R^2 = 97.09%) is better than the latter method (R^2 = 92.5%).
- Thus it can be concluded on the basis of the overall performance from both experimental and predicted values, that the double-electrode HTS method is better than the single-electrode HTS method, particularly with respect to grade and recovery.

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ACKNOWLEDGEMENTS. We thank CSIR-Institute of Minerals and Materials Technology, Bhubaneswar for permission to carry out this study.

Received 9 November 2018; accepted 26 June 2020

doi: 10.18520/cs/v119/i4/695-699

Parasitism ecology of sandalwood (*Santalum album* L.) for commercial production in the semi-arid tropics

Doddabasawa[1,*], B. M. Chittapur[2] and R. Lokesh[1]

[1]College of Agriculture, Bheemarayanagudi, Yadgir 585 287, India
[2]Directorate of Extension, University of Agricultural Sciences, Raichur 584 102, India

Successful establishment of a sandalwood plantation is rather difficult due to its complex parasitism ecology and unique silvics of the host species. The present study was therefore undertaken to understand the parasitism ecology of sandalwood under natural population in the semi-arid tropics, covering the north-eastern dry zone of Karnataka, India. Sandalwood was found to parasitize on nine different tree species belonging to four families dominated by Leguminosae (six tree species), and the maximum associations occurred with *Acacia nilotica*. Sandalwood tree requires long-term suitable host not only for mineral nutrients replenishment, but also for water supplementation to maintain plant water potential and minimal composition in above-ground parts apart from sufficient sunlight. Therefore, selection of suitable host assumes significance. *A. nilotica* and *C siamea* are preferred hosts, particularly at planting distance of 2.5 m in the semi-arid tropics of India. A planting geometry of 6 m × 6 m or 5 m × 5 m with sandalwood between the host plants at 2.5 to 3.0 m is ideal.

Keywords: Ecology, host species, parasitism, sandalwood, semi-arid tropics.

SANDALWOOD (*Santalum album* L.) belonging to the family Santalaceae is an evergreen, small to medium-sized hemi-root parasitic tree species endemic to peninsular India[1]. It is one of the precious and highly valued tree species known for its fragrant heart wood and oil[2,3]. The oil is extensively used in highly valued perfumery, cosmetics and medicine. Sandalwood also has religious significance and the wood is used in the handicrafts industry[4].

India is the major exporter of East Indian sandalwood and accounts for 90% of the total global production. However, production has decreased from 4000 to 500 t/yr in the country, whereas the global demand for sandalwood is between 5000 and 6000 t/yr (ref. 5). This gap has increased the price of sandalwood in the national and international markets by several folds. The decreasing production in India is mainly attributed to factors like illicit felling, forest fires, spike disease, poor natural regeneration, high demand in both national and international markets, and indiscriminate harvesting of trees by uprooting as oil is present in both heart wood and roots[1,6,7].

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

In order to increase sandalwood production and reduce the pressure on existing natural populations, the Governments of Karnataka and Tamil Nadu have liberalized the policy on growing sandalwood on private lands by amending Forest Act 2001 and 2002 respectively. Further, the fact that it can easily adopt to diverse climatic and edaphic conditions has attracted farmers and corporates to take up sandalwood plantations on a commercial scale[8].

However, regeneration and establishment of sandalwood plantations have been mostly unsuccessful because of the poor understanding of its parasitism ecology, i.e. sandal–host relationship[9]. Being a hemi-root parasite, sandalwood has unique and complex silvicultural characteristics[10]. Poor understanding of silvics of sandalwood and its parasitism ecology are considered as major constraints in the unsuccessful establishment of plantations. Sandalwood initially requires shade and later abundant light for its growth and development. It coppices well and produces root suckers. However, being a hemi-root parasite, it requires a host for survival, particularly for water and mineral nutrients despite being capable of photosynthesis[11]. Further, it is specific in choosing compatible partners in nature. Sandalwood is a known parasite of more than 300 species from grasses to trees, and even other sandal trees (self-parasitism)[12,13].

Interestingly, differential growth was observed with different hosts, and legumes were preferred over non-leguminous species[14–16]. However, such studies were mainly restricted to seedling stage and only a few were at field scale under natural conditions. The complexity of process of the parasitism makes it difficult, time-consuming and laborious. Therefore, the present study was conducted under natural ecosystem to understand the nature of parasitism and developmental mechanism in the semi-arid tropics.

The study was carried out at Bheemarayanagudi, Yadgir district, Karnataka, during 2019–20. The climate is semi-arid with short monsoon, mild winter and hot summer. The average annual rainfall is around 750 mm, and minimum and maximum average annual temperatures are 18.6°C to 32.5°C respectively; the mean elevation ranges from 350 to 680 m amsl. The soils are deep to very deep black and medium black in major areas, while sandy loam and light textured soils are also found in some pockets. However, the study was undertaken at 2 km radius of Bheemarayangudi, with abundant natural populations of sandalwood. The parasitism ecology of sandalwood was studied on trees having minimum of 10 cm girth normally and in perched condition, the closest host species were considered as host plants. The distance of sandalwood trees from the host plant was measured. Besides, height and girth of saplings and trees of sandalwood were measured using a multimeter and measuring tape, and volume of the saplings and trees was calculated using the non-harvestable method as follows[17]

$$V = \frac{g^2}{4\pi} \times h,$$

where g is the girth at breast height (cm) and h is the height (m).

Further, secondary data on hosts published in the literature were used to assess possibilities of association of sandalwood. The data collected were subjected to univariate analysis, correlation and one-way ANOVA at a significance level of 0.05. Further, to determine the difference between the means, post-hoc test was performed using Duncan's test at significance level of 0.05 using SPSS version 20.0.

In this study, sandalwood parasitized nine different tree species belonging to four families. Majority of them belonged to Leguminosae (six tree species), and one each to Meliaceae, Lamiaceae and Arecaceae (Table 1). This shows that sandal prefers leguminous plants for parasitism over non-leguminous plants, as these may help meet its nutrients requirement, especially nitrogen, and other factors such as thin and watery skin roots of Leguminosae family which probably facilitates haustorial connection.

Among the Leguminosae tree species, maximum association was observed with *Acacia nilotica* (babul; 16), followed by *Prosopis juliflora* (honey mesquite) whereas lower association was observed with *Albizia lebbeck* (Indian siris). This indicates parasitism specificity even in the same plant family. Probably host characteristics congenial for parasitism take precedence over other plant characteristics, viz. nodulation, extensive lateral roots, sparse crown, translocation efficiency of mineral nutrients and higher water use efficiency (Table 2). For instance, in several northeastern states in Brazil, roots grow as deep as 53 m and *P. juliflora* reportedly enriches the soil with organic matter, prevents excessive drying up and supplies the soil with nitrogen by means of *Rhizobium* fixation, thus giving rise to micro-climate conditions in the area of cactus cultivation. Similarly, *A. nilotica* species have a long taproot system. As the growth advances, several lateral roots also develop at the end of the first season and subsequently the taproot and lateral roots cannot be easily distinguished. Thus these two form good hosts. However, the lower association of sandalwood parasitism with *A. lebbeck* might be because most of the atmospheric nitrogen fixed by the genus *Albizia* used for its own use and nodules formed were few, though bigger in size. Hence, *Albizia* tree was more frugal in translating nitrogen to the fast growing sandalwood (Table 2)[18].

Sandalwood is a root hemi-parasite and relies on the host for mineral nutrients and water. However, parasitism not only depends on the characteristics of the host, but also on the distance of association from the host. In the present study, significantly longer distance of association was recorded in *A. nilotica* (2.61 m) followed by *Cassia simaea* (2.20 m), whereas significantly lower distance of

Table 1. Parasitism ecology and performance of sandalwood with different hosts under natural population in the semi-arid tropics

Tree species	Family	No. of associations	Distance from the host tree	Girth (cm)	Height (m)	Volume (m^3)	No. of root suckers
Acacia nilotica	Leguminosae	16	2.61^{a} (± 0.57)	31.44^{a} (± 11.15)	5.37^{a} (± 1.63)	0.053^{a} (± 0.036)	0.25^{cd} (± 0.68)
Prosopis juliflora	Leguminosae	08	1.86^{bc} (± 0.49)	20.19^{bc} (± 06.75)	3.88^{bc} (± 1.09)	0.015^{b} (± 0.013)	1.25^{bc} (± 1.04)
Azadirachta indica	Meliaceae	13	1.05^{d} (± 0.16)	12.54^{c} (± 02.10)	2.54^{cd} (± 0.60)	0.005^{b} (± 0.003)	0.00^{d}
Tectona grandis	Lamiaceae	12	1.37^{cd} (± 0.57)	16.96^{bc} (± 04.76)	3.08^{bc} (± 0.45)	0.008^{b} (± 0.005)	2.33^{a} (± 1.23)
Cocos nucifera	Arecaceae	06	1.53^{cd} (± 0.50)	17.40^{bc} (± 04.47)	2.93^{cd} (± 0.76)	0.008^{b} (± 0.005)	0.00^{d}
Albizia lebbeck	Leguminosae	03	1.23^{cd} (± 0.25)	14.00^{c} (± 02.18)	2.40^{d} (± 0.30)	0.004^{b} (± 0.002)	0.00^{d}
Leucanea leucocephala	Leguminosae	05	1.80^{bc} (± 0.57)	20.10^{bc} (± 06.04)	2.82^{cd} (± 0.91)	0.011^{b} (± 0.008)	1.00^{bcd} (± 1.41)
Inga dulce	Leguminosae	04	1.40^{cd} (± 0.47)	14.25^{c} (± 03.30)	2.48^{d} (± 1.09)	0.005^{b} (± 0.004)	2.00^{ab} (± 0.81)
Cassia siamea	Leguminosae	05	2.20^{ab} (± 0.67)	26.00^{ab} (± 11.00)	4.34^{ab} (± 1.02)	0.030^{ab} (± 0.029)	0.60^{cd} (± 0.89)
F-test			<0.005	<0.005	<0.005	<0.005	<0.005

association was noticed in *Azadirachta indica* (1.05 m) followed by *A. lebbeck* (1.23 m) (Table 1). The results are in agreement with those of Rocha *et al.*[19], who observed haustorial connections with other plants, including grasses up to 3 m distance. However, association with *A. nilotica* might be due to its extensive lateral root system and sparse crown compared to *A. indica* and *A. lebbeck*. Further, sandal requires shade in the early stages and later abundant light for growth and photosynthesis. Hence, association at appropriate distance helps meet adequate water, nutrients and light requirements. Similar results were reported by Rocha *et al.*[20], that growth of sandalwood is not only dependent on association with suitable hosts but also on possible competition of above-ground resources such as light. In concurrence, Vijayakumar *et al.*[21] reported suppressed growth of sandal plants with fast-growing host plants in pot culture experiments.

Further, significantly higher girth (31.44 cm), height (5.37 m) and volume (0.053 m^3) of sandalwood were observed in association with *A. nilotica* followed by *C. siamea*, whereas significantly lower girth (12.54 cm), height (2.54 m) and volume (0.005 m^3) of sandalwood were recorded in association with *A. indica* followed by *A. lebbeck*. This indicates that the parasitic growth of sandalwood not only depends on leguminous host, but also on other characteristics of the host plant such as water use efficiency, lateral root system, sparse crown, aggressive growth, allelo-chemicals released from litter, nodulation and sap flow of xylem tissue. Hence in the present study, better growth and performance of sandalwood were found in association with *A. nilotica* compared to other species. Lesser growth was observed in association with *C. siamea* compared to *A. nilotica*, which could be due to non-nodulation in the former (belongs to family Leguminosae but does not fix atmospheric nitrogen) (Table 2). Our results are in agreement with Xinhua *et al.*[22], who observed significantly higher net transfer of nitrogen from host plant *D. odorifera* to hemi-parasite sandalwood under effective nodulation. Similar observations were also made by Subbarao *et al.*[23], regarding increased nitrogen content in sandal plants grown in association with nodulating *Cajanus cajana* and *Pongamia glabra* in pot culture. However, poor growth of sandal with *A. indica* is due to its dense crown and lower water-use efficiency, and being non-leguminous in nature, it could not supply the required nitrogen (Table 2). Further, poor performance of sandal was also recorded in association with leguminous species *A. lebbeck*. This might be due to the fact that although *A. lebbeck* is able to fix atmospheric nitrogen, most of it is used by the species itself due to its fast-growing nature. The gregariousness also causes lot of shading of associated species.

Further, among the non-Leguminosae species, performance of sandalwood was found to be good with teak and coconut compared to neem. This might be due to sparse crown, translocation of phosphorus and lateral root system, higher water use efficiency of teak. Similarly, coconut having good lateral roots, especially in the shallow zone, sparse crown and higher water-use efficiency helped the associated parasitic sandalwood (Table 2).

Thus, the performance of sandalwood not only depends on host efficiency of mineral nutrients and water, but also on the competition for above-ground resources such as light which would be critical for growth. Our findings are in agreement with those of Rocha *et al.*[20], who observed significantly higher water potential (–0.85 MPa) in sandal grown with host compared to that without host (–1.27 MPa), and higher leaf nutrient content in sandal grown with host (N 2.6%, P 0.24% and K 2.31%) compared to that without host (N 2.48%, P 0.16% and K

Table 2. Characteristics of host plants parasitized by sandalwood under natural population in the semi-arid tropics

Host species	Family	Effective formulation of nodulation	Characteristics of species	Water-use efficiency of trees (kg/cm)*
A. nilotica	Leguminosae	Present (specificity to rhizobium)	Extensive later roots, sparse crown, slow-growing nature	45.00*
P. juliflora	Leguminosae	Present (specificity to rhizobium)	Exotic and fast growing , sparse crown	37.60*
A. indica	Meliaceae	Absent	Dense crown, slow growing	13.70*
T. grandis	Lamaiaceae	Absent	Deciduous, fast growing, sparse crown and high water requirement	Not found
C. nucifera	Aracaceae	Absent	Sparse crown, extensive lateral root system that at depth of	Not found
A. lebbeck	Leguminosae	Present (non-specific to rhizobium)	Fast growing, smaller number of nodules and non-traslocation of N to dry matter	Not found
L. leucochepala	Leguminosae	Present (specificity to rhizobium)	Exotic and extensive growth and prolific regeneration	Not found
I. dulce	Leguminosae	Present (specificity to rhizobium)	Exacting species, sparse crown a	11.9*
C. siamea	Leguminosae	Absent	Extensive lateral roots and moderate crown	21.5*

*Water-use efficiency was obtained from the study conducted by Tomar *et al.*[27] on the performance of 31 tree species and soil condition in plantations established with saline irrigation.

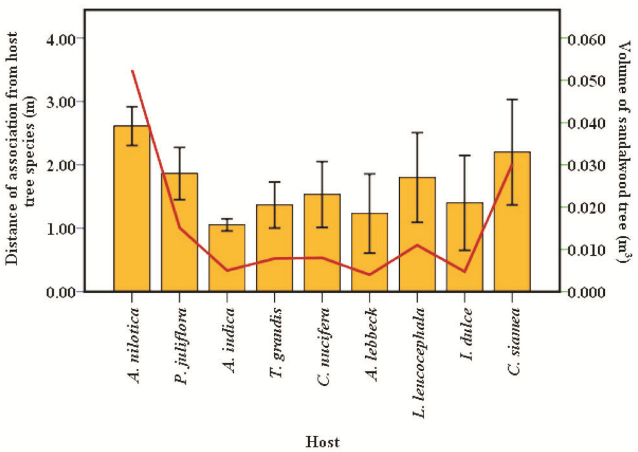

Figure 1. Performance of sandalwood tree as influenced by host and distance of association.

1.68%). Further, they reported that sandal not only depends on host for mineral nutrients, but also for maintaining its water potential. Some studies indicated better plant water status of sandal grown in association with a host[21,24,25].

In this study, we also noticed occurrence of root suckers. Sandalwood produced root suckers when it did not get sufficient mineral nutrients and water, mainly resulting in self-parasitism. This might be because young roots of sandalwood root suckers form an association with roots of even small plants like grasses, thereby trying to meet the nutrients and water requirements of the mother tree. Thus sandal becomes a walking tree in search of suitable host plants for survival. This is in conformity with the results of Fox and Brand[26], who observed extension of sandalwood lateral roots up to >20 m from the mother tree. However, in the present study significantly higher number of root suckers were observed in association with teak (2.33) followed by *Inga dulce* (2.00), whereas there were no root suckers in association with neem, albizia and coconut (Table 1). This might be due to the fact that teak is a non-leguminous species and reverse translocation of phosphorus from parasite to host plant could have occurred. Rocha *et al.*[19] also reported reverse translocation of nutrients from parasitic sandalwood to host plants, particularly of phosphorus from sandalwood to teak to the tune of 34.89% and up to 26% in casuarina. However, in case of *I. dulce*, it might be due non-extensive root system and lower water use efficiency (Table 2). However, lower number of root suckers in association with neem and albizia may be attributed to dense crown and non-nodulation characteristics, whereas in case of coconut it may be because of extensive lateral root system, wherein sandal might have been associated with lateral roots in multiple ways.

The present study indicates that the performance of sandalwood depends on the host characteristics such as formation of nodulation (leguminous), thin and watery lateral root system, sparse crown, slow-growing nature, translocation of nutrients, sap flow of xylem tissue and higher water use efficiency. Further, the influence of distance of association between parasite and host on the growth of sandalwood has been observed. The distance of association between parasite and host eliminates competition for above-ground resources, especially light. Hence, while establishing commercial sandalwood plantations, one should select the best host and with suitable planting geometry in order to reduce above-ground competition for its growth, one can even avoid formation of root suckers.

A. nilotica was found to be the best host among tree species followed by *C. siamea*. Better growth of sandalwood occurred when the distance of association was about 2.6 m away from the host (Figure 1). Hence, in the semi-arid tropics, sandalwood cultivation could be taken up either with *A. nilotica* or *C. siamea* as the host at a planting geometry of 6 m × 6 m or 5 m × 5 m with sandalwood in the centre at 3 or 2.5 m respectively, between the host plants. Few studies suggested the effectiveness of planting sandalwood at 2.5 m within the row of host plants planted at 4 m × 5 m; sandalwood planting at 6 m × 3 m spacing with amla (*Phyllanthus emblica*) as host at the same spacing in quincunx method of planting with density of 555 plants/ha each and sandalwood planting at 4 m × 4 m spacing with casuarina as host at the same spacing in quincunx method of planting with density of 625 plants/ha each[8].

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Received 22 October 2019; accepted 22 June 2020

doi: 10.18520/cs/v119/i4/699-703