Monograph

Acacia senegal

[A multipurpose gum yielding tree for agroforestry]

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Disclaimer:

The monograph on *Acacia senegal* has been prepared in academic spirit to provide a well compiled information on biological description, regeneration, silvics, integration in agroforestry and utilization of *Acacia senegal*. The information in the document is based on primary observations and secondary information from published literature.

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FOREWORD

Acacia senegal, known as *Senegalia senegal*, is a significant tree species found in the dry tropics, renowned for its valuable gum as 'gum arabic'. It is native to various regions of Africa, including Kenya, and has been introduced and naturalized in several other countries such as Australia, Egypt, India, Pakistan, Puerto Rico, South Africa, and Virgin Islands of US. In India, it is found across the rangelands and grasslands of arid and semi-arid regions in states like Rajasthan, Gujarat, Haryana and Punjab. The gum arabic produced by *Acacia senegal* is of immense economic importance, with approximately 90% of the world's gum arabic coming from this species. Sudan stands out as the major producer, particularly from the region of Kordofan. However, in India, the production of gum-arabic falls short of domestic demand, necessitating imports from countries like Sudan and Nigeria. Despite the increasing global demand for natural gums and resins, India is witnessing a decline in their production. This decline can be attributed to various factors, including unorganized harvesting methods and excessive tapping of trees, leading to the depletion of the resource base.

Integration of *Acacia senegal* on farmland in agroforestry is likely to increase production of gum-arabic and provide an alternate option of livelihood to smallholders. Besides, it may help farmers to diversify and use available land and other resources efficiently to achieve resilience against climate related risks. ICAR-Central Agroforestry Research Institute has developed agroforestry models based on gum-yielding trees and encouraged farmers for adopting *Acacia senegal* on farmlands, particularly in Bundelkhand. At this juncture, in view of the accelerated popularity and acceptability of *Acacia senegal* among farmers, it was considered necessary to compile all relevant scientific information at one place in the form of a monograph.

I congratulate the authors for bringing out the monograph of *Acacia senegal*, which is a comprehensive documentation of biological description, regeneration, silvics, integration in agroforestry and utilization. I believe this monograph will be a single-window source of information to the stakeholders.

Place: New Delhi
Date: 12-03-2024

(Himanshu Pathak)

Preface

Acacia senegal or *Senegalia senegal* a member of Fabaceae, is a small tree of 3-8m in height with umbrella-shaped crown known for producing gum arabic. It is widely spread in tropical Africa, Australia, Egypt, India, Nigeria, and other arid and semi-arid regions of the world. The natural exude from the tree constitute world's 90% trade of gum arabic with Sudan as the key producer holding major share (>80%) in the international market. India produces meagre quantity of gum arabic (~ 800 metric ton) compared to world production and consumption of 60,000-70,000 metric ton. Gum arabic finds application in various important industries like food & beverage, paper, textile, cosmetics, medicines, pharmaceuticals etc. The gum arabic trade has significant bearings on the economies of the African countries, however, frequent and severe drought disrupt the market. Secondly, overexploitation of existing trees causing decline in production of gum arabic and its trade. India, with significant area under arid and semi-arid zone suitable for raising large plantations of *A. senegal*, has good opportunity to capture market of gum arabic besides meeting its domestic requirements. There is worldwide call for increasing artificial plantations of the *A. senegal* by extending the tree on farmland as agroforestry for increasing resource base of gum arabic and also achieving climatic resilience in agricultural production system.

ICAR-Central Agroforestry Research Institute, Jhansi (ICAR-CAFRI) has taken research initiatives and developed some agroforestry models based on gum arabic for extension on farmland in semi-arid regions of Bundelkhand and other similar areas. Other researchers have also advocated for integration of gum arabic tree in agroforestry in arid and semi-arid regions of India and the world. Hence, it was felt necessary to compile all the relevant scientific information in the form a monograph on *A. senegal*.

The information embodied in this monograph are based on review of published literature and systematic research output at ICAR-CAFRI, Jhansi. The whole text has been divided in nine chapters. After a brief introduction as chapter one, the second chapter deals with the taxonomic details and chapter three discuses germplasm and genetic improvement aspects. The silvicultural characteristics, regeneration, and tree growth and yield are dealt in chapter four, five and six, respectively. Chapter seven describes *A. senegal* based agroforestry systems and chapter eight cover aspects of utilization. Summary and way forward has diction in chapter nine.

The authors express their gratitude to Secretary (DARE) and DG (ICAR) and DDG (Natural Resource Management) for their constant support, encouragement and constructive suggestions. The authors are highly indebted to the farmers for adopting *A. senegal* based agroforestry models on their farms and providing valuable feedback for research. Also, the cooperation and generous help extended by all scientists and colleagues is thankfully acknowledged.

We hope that this monograph will educate agroforestry researchers, foresters, extension workers and other stakeholders for scaling up *Acacia senegal* on farmlands.

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Chapter 1 Introduction and Distribution

Introduction

Acacia senegal (L.) Willd. is an important gum-yielding (gum-arabic) tree species. Its scientific name has recently been rechristened as *Senegalia senegal* (L.) Britton). Kyalangalilwa *et al*. (2013) separated *Acacia sensu lato* into two new genera, namely *Senegalia* and *Vachellia. Senegalia senegal* is now the accepted name of what was formerly called *Acacia senegal*. It is a small tree of 3-6m in height with umbrella-shaped crown. It is a typical tree of Sahel in Africa from Senegal to red sea and essentially limited to the area between 11^0 and 16^0 North with a wide range of rainfall (100 to 800mm). *Acacia senegal* was first described as *Mimosa senegal* L. (Ross, 1975) before it was shifted to the genus *Acacia. Acacia senegal* is a typical multipurpose tree species of dry tropical areas (arid and semi arid zone). It is highly valued for producing gum arabic, planting on farmland as agroforestry, controlling desertification and other multiple uses (El-Amin 1973; ICRAF 1992; Hines and Eckman 1993; Raj *et al*., 2015). It exudes gum called 'gum-arabic', which is an important commercial produce and contributes significantly to the economy of African countries (Ballal *et al*., 2005; Fadl and Sheikh, 2010). World's 90% *gum-arabic* is produced from *A. senegal*. Kordafan, a province of central Sudan, produces approximately 90% gum-arabic. In India, its production is insufficient even for domestic consumption; hence, imported from Sudan and Nigeria. In India, natural as well as planted stands of *A. senegal* are present in desert and arid regions of Rajasthan, Gujarat, Haryana and Punjab (Raj *et al*., 2015). Bundelkhand region of Central India can host large scale plantation of *A. senegal* as it is situated in semi-arid tropics (Singh *et al*., 2017) and the climatic conditions are suitable for production of *gum-arabic* which may provide livelihood security to marginal farmers. Recently, as one of the partner of Indian Council of Agricultural Research (ICAR) network project "harvesting processing and value addition of natural resins and gums, ICAR-Central Agroforestry Research Institute (ICAR-CAFRI), Jhansi has taken new research initiatives to develop suitable agroforestry models based on gum-yielding trees particularly *Acacia senegal* for semi-arid region of Bundelkhand in Central India. Extension of *Acacia senegal* on farmlands as agroforestry would not only increase production base of gum-arabic but also help farmers to achieve resilience against climate related risks. In view of the accelerating popularity and acceptability of *Acacia senegal* among farmers, a need was felt to compile all the relevant scientific information in the form a monograph.

Distribution

Acacia senegal thrives well in arid and semi-arid regions with a low rainfall of 100-250 mm (Ballal, 1991). It is highly drought tolerant species and can survive prolonged dry periods of 8-11 months with maximum temperature reaching 50^{O}C and strong winds (Fadl, 2013; Hocking, 1993; Jindal *et al.*, 2000). However, it is sensitive to frost. It prefers well drained soils and can grow on slightly loamy sands (Obeid and Seif el Din, 2006). It is native to Angola, Botswana, Burkina Faso, Eritrea, Ethiopia, Gambia, Kenya, Mali, Mozambique, Namibia, Niger, Nigeria, Senegal, Sudan, Tanzania, Uganda, Zambia and Zimbabwe (Pichi-Sermolli, 1955). The species is distributed throughout the arid and semi-arid parts of Africa including Kenya. However, it is exotic but naturalized to Australia, Egypt, India, Pakistan, Puerto Rico, South Africa, and Virgin Islands of the United States of America (Eisa *et al.*, 2008) (Figure 1). In India, it occurs mostly on rocky, gravelly and skeletal soils, and is widely distributed as interspersed species in most of the rangelands and grasslands in the arid and semi-arid regions (Prasad *et al.*, 2015). It is also found in the western and southern parts including Delhi, Rajasthan, Gujarat, Panjab, Haryana, UP *etc.* (Bharucha, 1955; Parker, 1956; Ram, 2011) in association with *Capparis decidua*, *Euphorbias*, *Anogeissus pendula, Boswellia serrata, Prosopis juliflora* on the sandy, rocky and alkaline soils of the hills (Qadri, 1957; Chaudhri, 1957). It is observed in Desert Thorn Forest (6B/C1), *Euphorbia* scrub (6B/DS2) and *Acacia senegal* forest (6/E2) (Champion and Seth, 1968).

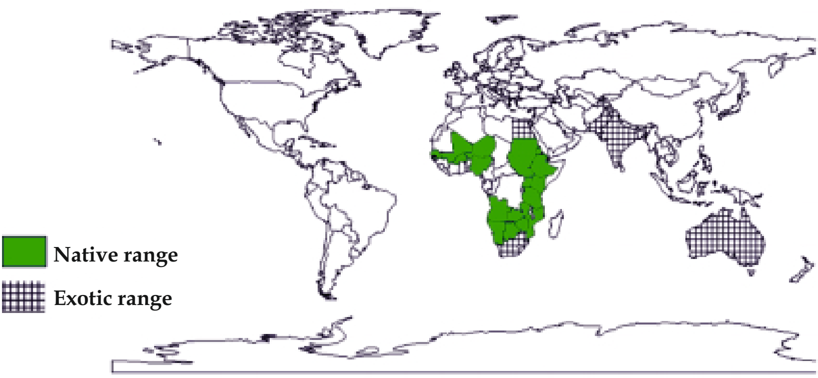


Figure 1. Distribution of *Acacaia senegal* in the world (https://www.feedipedia.org/content/gum-arabic-tree-acacia-senegal-worldwide-distribution)

Acacia senegal has wide adaptability to varying topography and soil conditions as evidenced by significant correlations of its growth and abundance with topography, soil texture, soil structure, soil consistency, maximum water holding capacity, wilting coefficient (sub-surface soil), soil carbonates (surface soil) soil pH (surface soil) and community associates. The best habitat for *Acacia senegal* is between 100 and 1700 m altitude with mean annual temperature between -4 and 48 ^{o}C and mean annual rainfall of 300-450 mm. Because of drought-tolerance, *A. senegal* is the characteristic species of the drier parts of Anglo-Egyptian Sudan and the northern Sahara, but also found throughout the vast area from Senegal to the Red Sea, extending up to eastern India (Obeid and Seif El Din, 1970; Bationo *et al.*, 2011). It extends southwards to northern Nigeria, Uganda, Kenya, Tanzania and southern Africa. *A. senegal* is associated with a wide range of vegetation types, from semi-desert grasslands to *Anogeissus* woodlands and prefers clay plains and rocky hill slopes (Gray *et al.*, 2013).

Normally, *A. senegal* performs well on nutrient poor soils including fossils, dunes, loamy soils, lithosols and heavy clay soils. It occurs predominantly on the sandy sedimentary plains and rocky hill slopes. The soil characteristics that influence its distribution in the plains include texture, clay content, water holding capacity and salinity (Doyo, 1994). The habitat soil conditions may vary from coarse-textured, deep sandy soils to dry, rocky, slightly acidic to moderately alkaline soils. However, *Acacia senegal* is intolerant to water logging. In many countries the trees of *A. senegal* observed both in the wild and in cultivated farm- mainly on sandy hills, but also reportedly grows well in cotton soil of Sudan (Bekele-Tesema *et al.,* 1993).

Chapter 2

Taxonomy and Phenology

Acacias belong to family Fabaceae (Mimosoidae). *Acacia* Mill. is a very large genus containing trees, shrubs and climbers. The genus *Acacia* find its greatest expression in Africa and Australia but, the Indian sub-continent has also a fairly good representation. There are more than 1200 species of *Acacia* (Simmons, 1981) occurring naturally in all continents except Europe and Antarctica. Currently 729 species are recognized in Australia and about 120 taxa are yet to be described (Maslin, 1981). Among recognized species, 115 occur in Africa (Ross, 1973; 1981) and remainders are in Asia (including China). In India *Acacia* is one of the five dominant genera of legumes and finds second place with 94 species. The trees, shrubs and climbers contained in genus *Acacia* Mill. are armed with prickles or stipular spines. Flowers are small, yellow or white in globose heads or cylindrical spikes with numerous scaly paleae between the flowers. Leaves are usually bi-pinnate. Calyx and corolla are usually tetra to penta-merous. The calyx is campanulate or cup shaped, toothed or lobed. Petals are indefinite, free, generally very numerous, not exceeding 1.25cm in length, Anthers are minute. Pods are dehiscent/indehiscent with compressed seed. The genus *Acacia* has been sub-divided into three sub-genera namely i) sub-genus *Acacia*, ii) sub-genus *Heterophyllum* and iii) sub-genus *Aculeiferum* (Guinet and Vassal, 1978). The occurrence of sub-genus *Acacia* is mainly in Africa but also found in Asia, South America and to limited extent in Northern Australia (Tindale and Roux, 1975; Simmons, 1981). By belief, the ancestral forms of angiosperms and acacias evolved in the tropical low land forest of West Gondwanaland (Raven and Axelrod, 1974; Beadle, 1981). Speculation has extended to dispersal routes within Africa (Ross, 1981) and Australia (Beadle, 1981) after break up of Gondwanaland into separate continents. Beadle (1981) suggested that a few species arrived in Australia before separation and subsequent species evolved and spread southwards from tropical Northern Australia. However, Tindale and Roux (1974) suggested that Eastern Australia was the center of origin of Australian acacias. Hopper and Maslin (1978) opined that there has been major proliferation of species presently occurring in South western areas of West Australia. Some species are also supposed to have under gone long distance dispersal by sea.

Acacia senegal belongs to the genus *Acacia* sub-genus *Aculeiferum,* which is widely distributed in tropical and sub-tropical regions of the Americas, Africa and Asia (Ross, 1968). The great variability in the species, however, has led to difficulty in its taxonomic delimitation and hence, a long list of synonyms. Four varieties have been recognized, which are: var. *senegal* Brenan, var. *kerensis* Schweinf., var. *rostrata* Brenan and var. *leiorhachis* Brenan. However, these are surrounded by continuous contradictions, disagreements (Brenan, 1959; Ross, 1979) and difficulty in assigning herbarium specimens to a variety without adequate field notes about the habit and habitat (Fagg and Allison, 2004). The botanical variation is based on morphological characters that differentiate the varieties namely: presence or absence of hair on the inflorescence axis, color of the axis, shape of pod tips, number of pinnae pairs, occurrence of a distinct trunk, and shape of the crown (Brenan, 1983; Ibrahim *et al.*, 2014). The four varieties are further reported to develop into different growth forms (Fagg and Allison, 2004) ranging from low multi-stemmed shrubs (var. *kerensis* and var. *rostrata*), low bush with whip-like stems (var. *leiorhachis*), small trees (var. *senegal* and var. *rostrata*) to larger trees (var. *senegal* and var. *leiorhachis*). The numerical taxonomic study on three varieties is based on only vegetative characters and it was not able to provide characters that can be used to identify herbarium specimens. Mulumba and Kakudidi (2011) studied numerical taxonomic principles and multivariate analysis based on 69 characters of *Acacia senegal* derived from growth form, branchlets, leaves, flowers, pods and seed. The wide variation within var. *senegal* has been splited into three recognizable variants and that of var. *leiorhachis* into two. The most important characters for differentiating the taxa include leaf breadth and length, pinna length and its ratio to pinna breadth, number of leaflet pairs, petiolar gland shape, petiolar and rachis gland size, stem and branch bark texture, stem and branchlet colour, under-bark colour for stem and branches, pod apical shape, growth form, crown shape, and prickly state of leaves.

Morphological Characters

Acacia senegal (L) Willd. is deciduous in nature and grows as shrub and/or a medium sized tree depending on the habitat. Generally, the tree grows up to height of 3-6m with umbrella shaped crown; however, it can attain height up to 7-8m or even 12m in most conducive environment. The trunk may vary in diameter up to about 30 cm. Ramification from main trunk at 1-1.5m height, much branching with many upright twigs with wider spreading in the upright part. The bark is greyish-white although in old trees growing in the open it may be dark, scaly and thin, showing the bright green cambium layer just below the surface if scratched (Orwa *et al.*, 2009). Slash mottled red and white, prickles in triplets (Plate 1A) black curved like claws, leaves, small, bipinnate, 3-6 pairs of pinnae with 8-18 pairs of leaflet each. Flowers pedunculate while spikes clustered in pairs and triplets at leaf axils. Pods, flat and thin, mostly pointed at both ends containing 3-6 flat seeds, brown in color (Plate 1B).

Plate 1. Prickles in triplets (A) and mature pods (B) of *A. senegal*

Taxonomy

According to IT IS catalogue of life (April 2013), *Acacia senegal* is classified as following (Kyalangalilwa *et al*. 2013)

Kingdom	Plantae
Phylum	Tracheophyata
Class	Magnoliopsida
Order	Fabales
Family	*Fabaceae (Mimosoidae)*

Genus	*Acacia*
sub-genus	*Aculeiferum*
variety	*senegal*
Authority	(L) Willd.
Name	*Acacia senegal* (L) Willd.

Acacia senegal (L) Willd. belongs to family *Fabaceae* (*Mimosoidae*) with four main varieties namely Var-*rostrata* (Brenan), Var-*leiorhachis* (Brenan), Var-*kerensis* (Schweinf) and Var-*senegal* (Brenan, 1983; Cossalter, 1991). However, synonym(s) of this species are *Acacia circummarginata* Chiov; *Acacia oxyosprion* Chiov.; *Acacia rupestris* Stokes; *Acacia senegal* (L.) Willd. ssp. *senegalensis* (Houtt.) Roberty; *Acacia spinosa* Marloth & Engl.; *Acacia trispniosa* Stocks ex Boiss.; *Acacia verek* Guill. et Perr.; *Acacia volkii* Susseng; and *Mimosa senegal* L. It is a small tree, 3-6 m. tall, young shoots pubescent, old branches glaucous-grey, on older stems the bark peels off in thin flakes of a darker colour. Prickles in threes at the base of the petiole, two lateral ones nearly straight or slightly curved upwards, the third one recurved 5 mm long. Rachis 2.5-5 cm long, with glands between the lowest and upper most pair of pinnae. Pinnae 3-5 pairs, opposite, sometimes alternate, 1.2-2.5 cm long. Leaflets 8-15 pairs, 2-5 mm long, 1-1.5 mm broad, linear, obtuse, subsessile. Inflorescence-a pedunculate spike, peduncle 8-18 mm long, spike 5-10 cm long. Flowers sessile. Calyx 1.5-2.5 mm long, broadly campanulate, glabrous. Corolla 4 mm long. Stamens indefinite, filaments 6-7 mm long. Pod 5-7.5 cm long, 1.7-2.5 cm broad, thin, flat, almost straight, shortly stipitate, tip with a slightly curved beak. Seeds 5-6, disc like, almost circular, ovate to linear-ovate, 6-9 mm long, 5-8 mm broad, with a U shaped depression on either side, smooth, dark brown to greyish green in colour.

Pollination

Acacia senegal flowers are cross-pollinated and visited by number of insect for collecting nectar and pollen (Joker, 2000). The most important pollinators are honey beeas and solitary bees.

Seed Setting and Dispersal

Fruiting takes place during August to October. Fruits contain 3 to 5 seeds per pod. It has low fruit set ratio due to a high degree of self-incompatibility and largely depends on cross pollination by insects for fruit setting. The wind shakes seeds from the dehiscent pods, whereas sheet wash and grazing animals extend the seed dispersal range (Plate 2 A, B & C).

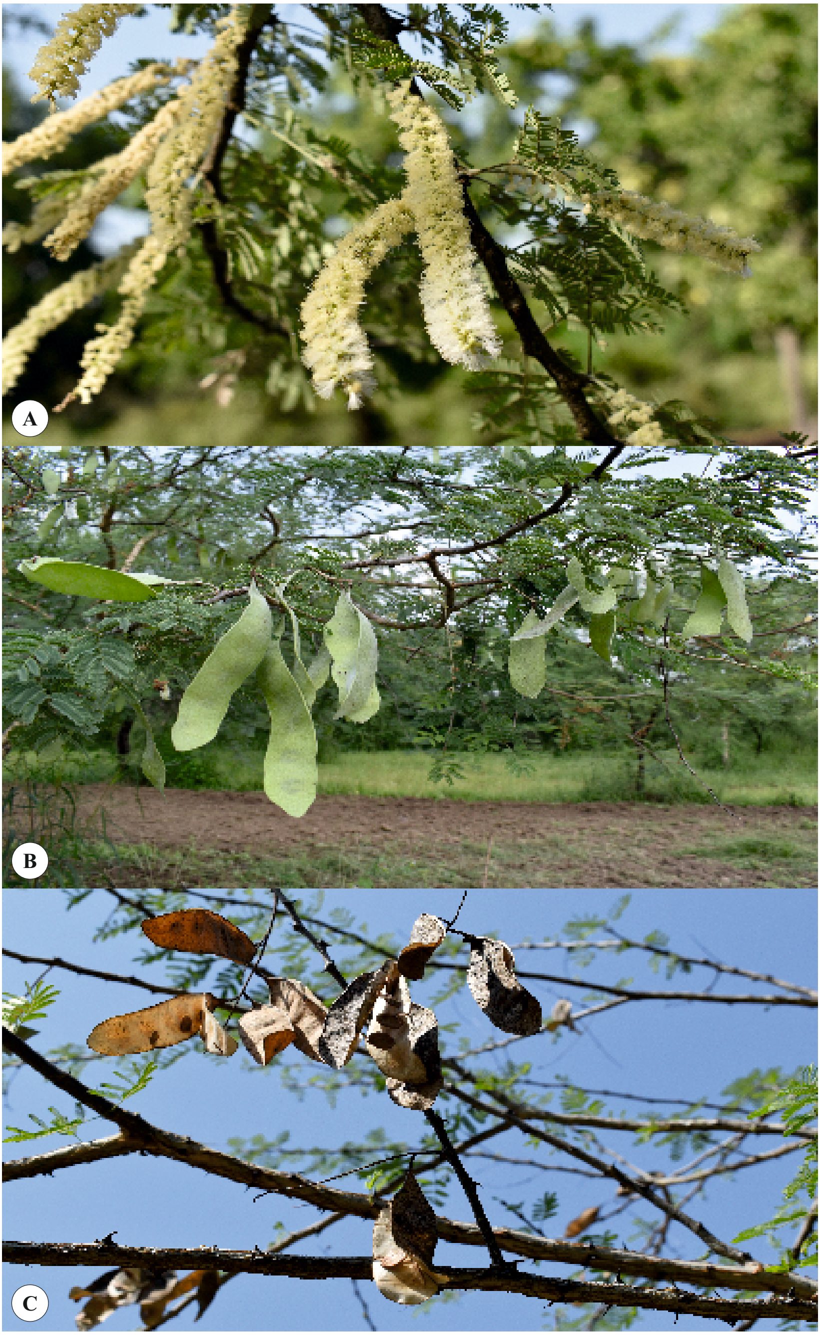


Plate 2. Flowering (A), pod formation (B) and dehiscent pods (C) of *A. senegal*

Phenology

In general, flowering in *Acacia senegal* begins just before or at the beginning of the rainy season when the leaves emerge and the seed mature in the dry season (Joker, 2000). The effect of variety of flowering time has been reported in areas with more than one variety and it shows wide variations in flowering and fruiting time throughout the world. For example, flowering starts from June to July in Sudan, December to January in South Africa, February to March in Pakistan, and August to December in India. Fruits ripen in January in Burkina Faso, July-September in Kenya, August in Pakistan, October in South Africa, and November-December in southern and central Niger (Sahni, 1968; Noad and Birnie, 1989; Fagg and Allison, 2004).

Chapter 3

Germplasm and Genetic Improvement

Genetics and Tree Improvement

Acacia senegal shows wide genetic variability among the provenances (Fakuta *et al*., 2015) and because of wide genetic variations, there is need of germplasm exploration, collection and field evaluation (Kananji, 1993; Odee *et al*., 2012; Djibo *et al*., 2017). Size of fruit and seed weight varies with region to region depending upon water availability and soil conditions (Tietema *et al*., 1992). The fruits from dry streams with loamy sand soil type are of bigger size while seeds per pod and seed weight are higher in hilly regions. Jindal and Singh (2003) studied morphological variation for seed characters of 25 *A. senegal* accessions in north-western India and reported mean pod length of 8.71 cm, ranging from 6.76 to 10.5 cm. Mean values were 5.02 for number of seeds per pod, 0.79 cm for seed length, 0.70 cm for seed width, 10 g for 100-healthy seed weight, 0.79 g for 100-infested seed weight, 4.9% for seed infestation percentage with bruchids, and 1.07% for percentage seed biomass loss. The maximum variation was observed for percentage bruchid infestation, followed by percentage loss in seed biomass.

To identify fast growing genotypes, seeds (germplasms) of eleven accessions were collected during 1985 from arid and semi-arid areas of Rajasthan. These germplamsms were evaluated during 1985 in the nursery and in the field by planting seedlings at the rocky rangeland management area, Bhopalgarh of the Central Arid Zone Research Institute (Jindal *et al.,* 2000). Nursery studies revealed that there were variations in seedling-related characters. The cotyledonary leaf length varied from 1.12 to 1.35 cm. Accession number 364 from Bar (Ajmer) showed maximum cotyledonary leaf length. Maximum germination (70.4%) was recorded for accession number 350, collected from rocky areas of Beriganga (Jodhpur); and minimum germination (42.8%) was recorded for accession number 359 belonging to rocky rangeland of the village Jhurli (Jodhpur). For three-month-old seedlings, shoot length varied from 11.9 to 25.6 cm and it was maximum for accession number 376. Mean root length was 34.0 cm and it was maximum for accession number 370, a collection from the market. Ratio of dry shoot and root weight, a parameter of balanced growth, was maximum for accession number 350 and 364 and it was minimum for accession number 369. They further reported that seeds of *Acacia senegal* of eleven different accessions showed large and random variation in germination and juvenile growth. This large random variation among these accessions could be due to the parent tree genotypes. The environmental conditions experienced by the parent plant during the seed development influence the dormancy in the seeds (Fenner, 1985), which also causes variation in seed germination and seedling growth. The differences in dormancy behaviour can usually be interpreted as an adaptation for staggering or delaying germination until the onset of a favourable season, hence; this character may be useful for the selection of genotypes for wasteland development, particularly in situations where seed broadcasting method is followed for afforestation.

A study by Jindal *et al*. (2000) reported that correlation coefficients between all possible pairs of 13 characters showed that the four characters, *i.e.* 100-seed weight, cotyledonary leaf length, cotyledonary leaf width and germination percentage, had no significant associations with other characters or among themselves, except between cotyledonary leaf length and cotyledonary leaf width that exhibited a positive correlation. Height in the nursery (*i.e.* shoot length at the 3-month stage) showed a positive relationship with height at subsequent years of growth, and it was significant at later stages of growth. Root length of three-months-old seedlings showed a negative relationship with tree height over different periods, showing that root-length selection at an early age may not be a good criterion for fast growth of the tree. This may be due to a favourable environment in terms of moisture availability at the nursery stage, which is not available when the plant is in the field. Dry shoot:root weight had a positive association with height, suggesting that accumulation of more biomass in the shoot portion at an early stage can give fast growing genotypes at later stages. The study concluded that in the case of *A. senegal*, selection for fast-growing genotypes can be made at two stages: (1) at the time of germplasm collection, by identifying plus trees with desirable characters such as straight bole, insect pest free, and from such soil types in which the plantation has to be done; and (2) at the juvenile stage *i.e.* in the nursery or from the second year onwards when the trees are in the field.

In Africa, improvement of wild *Acacia senegal* has been carried out through silvicultural methods primarily for production of gum arabic and to some extent for fodder, fuel wood and also for drought tolerance. Chiveu *et al.* (2009) studied genetic diversity in Kenyan populations of *A. senegal* based on morphological and molecular (ISSR) markers for improved gum production, whereas Assoumane (2009) characterized microsatellite markers for *A. senegal* and observed 11 polymorphic microsatellite loci specifically designed for *A. senegal* in 247 individuals from three populations from Niger. On an average, 10.9 alleles per locus were detected and expected heterozygosity ranged from 0.160 to 0.794, showing the ability of the markers to detect genetic diversity in this species. Using 10 RAPD and 5 ISSR primers, Josiah *et al.* (2008) observed a total of 55 polymorphic bands with an average of 3.6 polymorphic loci per RAPD+ISSR primer. In this mean Nei's gene diversity index for the populations was 0.283 and mean observed number of alleles per locus was 1.982 and showed that much of the genetic variation resided within the populations. Studies on the provenance variations indicated a wide difference in growth and biomass production in *A. senegal* seedlings of different origin (Raebild *et al.*, 2003; Gray *et al.*, 2013).

Larwanou *et al.* (2010) conducted a study to evaluate the performance of 11 *Acacia senegal* provenances in Niger, West Africa, grown on 2 different soil types. Among the provenances, 6 were from Niger, 4 from Mali and 1 from Sudan. The assessment was carried out with measurements of growth parameters (survival rate, height, diameter and basal area) as well as gum and fruit production at age 15. The results showed significant differences in growth parameters between soil types and provenances. The provenances from Mali had performed best, followed by the local Niger provenances. There were no significant differences in gum and fruit production between provenances, but it cannot be excluded that this was a result of limited power in the test of provenance variation in these traits. Survival of the provenances was correlated to the precipitation and the latitude of the origin, whereas basal area was correlated to latitude, and height was correlated to longitude/altitude at the origin. Recommendations could be made for genetic selection of two Mali provenances if growth is a desired character. They concluded that recommendations in terms of gum and fruit production must be based on a relative high number of sample trees as tree to tree variation within provenances may be large.

Wood Anatomy

Anatomy of wood is the characteristic feature of a species (Gupta *et al.*, 2017). In *A. senegal*, gum-arabic is formed in cysts in the inner bark of the branches and not in the wood. The gum cysts are formed first in the parenchyma of the phloem. In case of wounding, the gum is transported to the wounded site via new channels formed by degradation of the cells. Macroscopic characters indicate that sapwood is pale to creamy yellow, heartwood pale to dark brown, whereas microscopic characters are growth rings consisting of flattened marginal parenchyma or thick-walled fibres (Ghosh and Purkayastha, 1962; Hamid *et al.,* 2010). Vessels solitary, in pairs or radial groups, 70–200 µm; perforation plates simple; intervessel pits alternate, vestured, vessel-ray pits similar to inter-vessel pits. Fibres are with simple pits. Axial parenchyma is confluent (var. *leiorhachis*) or banded (var. *rostrata*), whereas rays are 1–5-and seriate, homogenous with an average height 270 µm (var. *leiorhachis*) to 420 µm (var. *rostrata*). Prismatic crystals are present in chambered axial parenchyma cells (Robbertse *et al.*, 1980). However, a significant negative correlation was found between the latitude and ray height of *A. karroo* wood specimens. Tree ring studies in the lowlands and highlands highlights the complexity of ring formation and indicates four major types of growth ring expression: anatomically not distinct rings, multiple rings per year, annual rings and multiple missing rings. Here complex tree growth behavior is associated with large-scale variations in precipitation regime (unimodal to multimodal) and relatively small-scale variations in tree sensitivity to water availability (Wils *et al.*, 2011). Osman and Abdelgadir (2013) studied the anatomy of *Acacia drepanolobium*, *A. nilotica* sbsp. *nilotica*, *A. nubica*, *A. seyal* var. *seyal* and *A. larta*, *A. mellifea*, *A. polycantha* subsp *campylacantha* and *A. senegal*. Significant differences were observed between the species for most of the quantitative anatomical characteristic. The exceptions were fibre diameter in both juvenile and mature wood and in vessel volume fraction. There is no evidence for differences in the qualitative anatomical structure between spinescent and non-spinescent group except in juvenile wood growth rings (Osman and Abdelgadir, 2013). Variations in leaflet anatomy has also been studied (Khalil and Siam, 2003), where xeric provenances had significantly higher stomatal density than the mesic. Though no significant difference in guard cells length among the provenances and water use efficiency were detected, some provenances were shorter in shoot and lower number of leaflets/pinna than the other provenances and showed the higher values for net photosynthesis rate, stomatal conductance and transpiration rate.

Chapter 4 Silvicultural Characteristics

Growth Habit

Acacia senegal is a small thorny tree and generally grows to a height of 3-6 m with umbrella shaped crown. In favorable conditions it grows beyond 7 m in height and can attain a maximum height up to 15 m. It is deciduous in nature, dropping its leaves during the dry season. The trunk may vary in diameter up to about 30 cm. The clear bole height ranges from 1 to 1.5 m before ramification in to 2-3 main upright branches. Many secondary and tertiary branches spread and give rise a rounded, flat-topped and umbrella shape crown (Orwa *et al.,* 2009). *Acacia senegal* is relatively slow growing, with a life span of 25 to 30 years. It yields 1 to 4 $m^3 ha^{-1} yr^{-1}$ at 25 years of age, depending on the site. This tree is adapted to a variety of arid sites and soils. It is aggressive and is easily established.

Seed Germination

The seeds of *A. senegal* start germinating when favorable conditions are available. The germination of seed is epigeal. The radicle emerges and moves downward. The hypocotyl elongates and cotyledons are pushed above ground. The growth and elongation of roots is faster than that of shoot. The primary tap root is long and thick. Development of numerous laterals results in strong anchoring root system. The seeds are orthodox and store well in a cool, dry, insect-free place. If seed is stored at 10°C with moisture content of 5-7%, its viability can be maintained for several years. Germination is improved if the seeds are soaked in cold water for 12-24 hours before sowing. It is a typical pioneer species and easy to propagate from seed. The germination is fast and uniform.

Seedlings

Young plants of *Acacia senegal* grow very fast and may attain a height of 75 to 100 cm in a year after transplanting in the field. In sites where soils are rocky and gravely the growth of seedlings is slow and poor. The seeds are sown in polypots or in 30 cm long tubes. Normally 2-4 seeds are placed in a tube and after 4-6 weeks, it is thinned to one seedling. Frequent root pruning is necessary in container plants as the tap root is fast growing. Planting out can take place after 4-6 months.

Root System

In *Acacia senegal* first and second order root (tap root and lateral roots) develops during germination period. At planting some time if tap root damages, the secondary roots regenerate and establishes the plantlets. It develops a good root system that stabilizes soil structure and enriches the soil with symbiotically-fixed nitrogen (Plate 3). Deep tap roots can develop when water is available at deeper zone allowing growth of the tree larger than normal (Gerakis and Tsangarakis, 1970).

Plate 3. Well grown root system of *A. senegal* after 3-years of planting in field

Coppicing

Acacia senegal coppices readily and re-growth occurs often from coppice. To manage a coppice, there is need to select about four dominant branches and removal of other smaller/weaker branches. These can further be reduced to two or three branches within the year.

Resistance to Drought, Frost and Salinity

Acacia senegal is hardy and drought tolerant, and known to survive prolong dry periods. The drought tolerance is said to be due to high proline content found in acacias. Several plant species including acacias are known to accumulate free amino acids especially proline, during moisture stress (Stewart *et al.*, 1966; Singh *et al.*, 1972). The accumulated proline tends to disappear on release of stress (Singh *et al.*, 1973). Full grown plants escape frost damages; however, young seedlings are susceptible to frost. Normally, the plants affected with frost re-sprout but, in extreme cases of damage they are killed. It grows well in soils from slightly acidic to alkaline in nature. The increased salinity reduces Zn, Cu, Mn and Fe accumulation in plants and thus affects the survival and growth of *A. senegal,* (Hardikar and Pandey, 2008). It cannot tolerate water logging and thrives well on well drain soils.

Site Factors

Acacia senegal has wide adaptability to varying topography and soil conditions. Its growth and abundance correlate well with topography, soil texture, soil structure, soil consistence, water holding capacity, wilting coefficient, soil carbonates, soil pH, community associates etc. Normally, *A. senegal* performs well on poor soils including fossils, dunes, loamy soils, lithosols and heavy clay soils. It occurs predominantly on the sandy sedimentary plains and rocky hill slopes. The soil characteristics that influence its distribution in the plains include texture, clay content, water holding capacity and salinity (Doyo, 1994).

Temperature

In its natural habitat, the summers are very hot, where maximum temperature may go up to 50°C. During winter mercury level dips below freezing point. This tree normally tolerates temperature range varying from -4°C to 48°C. The high temperature in summer poses no problem to this species.

Rainfall

Acacia senegal is drought resistant species and grows well in regions where mean annual rainfall ranges from 300-450 mm. It grows in lower rainfall areas also, but growth is comparatively poor. The plant grows well with faster rate under irrigated condition. The best habitat for *Acacia senegal* is between 100 and 1700 m altitude with mean annual rainfall of 300-450 mm

Ecological Association

A. senegal is associated with a wide range of vegetation types, from semi-desert grasslands to *Anogeissus* woodlands and prefers clay plains and rocky hill slopes (Gray *et al.*, 2013). It provides healthy ecosystem and habitat for many animals and birds (Plate 4).

Plate 4. Tree branches of *A. senegal* supporting nests of weaving birds

Chapter 5

Regeneration

Natural Regeneration

A. senegal can regenerate naturally. The species occurs in sandy desert and on rocky, gravelly and skeletal soils. It is widely distributed as interspersed species in most of the rangelands and grasslands in the arid and semi-arid regions (Prasad *et al*., 2015). Its large natural dense forest is unseen in India. Natural regeneration occurs mainly through seeds. Generally, the pods burst while still on the plant and seeds are blown away by the wind. Sometimes ripe pods of *A. senegal* fall on the ground which burst due to sun-drying and seeds are scattered. The fallen seeds are often buried in soil due to deposition of windblown sand, a common phenomenon in its natural habitat in sandy desert. The buried seed may germinate in early monsoon on availability of adequate moisture, which is required for germination.

A. senegal faces mainly two problems in its natural regeneration *viz.* poor germination due to burial of seeds and damping off of sprouted seedlings. The seed fails to germinate and emerge out if; it is buried at deeper layer. The possibility of burial of seed remains very high if wind velocity is high with dust storm. Often deposition of blown sand results in burial of seeds. On getting favorable conditions after onset of monsoon, seeds germinate and seedlings start growing. In the event of long dry spell of drought, mortality of seedlings occurs. Occasionally, excessive moisture or flooding particularly in low lying area also damage young seedlings. Annual weeds and grasses compete for moisture and nutrients with young seedlings, which often results in failure of seedling establishment. Thus, poor germination and environmental stress to young seedlings are the main constraints that make re-generation of *A. senegal* difficult in nature. Also, irregularity of rains and the frequent attack of the seeds by insects and rodents make natural regeneration in *A. senegal* unpredictable.

Artificial Regeneration by Seeds

In favorable conditions *A. senegal* regenerates naturally and grows well. Under drought and intense competition from grasses and weeds, the plant does not regenerate naturally. However, over-exploitation of natural stands by local inhabitants for seeds to be used as vegetable (*Panchkuta*) and gum exudation coupled with poor natural regeneration has necessitated its multiplication through artificial regeneration.

Artificial regeneration by direct seeding

Acacia senegal var. *senegal* can be easily propagated by seeds. In acacias artificial regeneration by sowing seeds directly in the fields is a common practice (Ghosh, 1977) and same can be implied in case of *A. senegal* too. The right period of sowing seeds in field is the early July after onset of monsoon rain. It is better to sow seeds early after the first monsoon shower when the surface soil is sufficiently moist. However, long spell of dry period after first shower may result in germination failure. To minimize the risk, it is better to sow seeds when monsoon has set in and the ground is moist. One kg seed of *A. Senegal* contains 7000–19,000 seeds.

Depending on methods of sowing the seed rate varies. Instead of broadcasting, dibbling of seed is preferable. Dibbling consists of digging of small pits, placing 3-4 seeds in each pit and covering them with thin layer of soil (1.0 cm). This is labor intensive as seeds have to be put in pits manually. The seed dibbler used for agricultural purposes can also be used for dibbling of *A. senegal* seeds for covering large areas. Seeds can also be sown in trenches having 30-45 cm cross section made 3-5 m apart. This method is beneficial in conserving the soil moisture and prolonging the moisture availability to young plants. In case of drought, a common phenomenon in arid areas, conserved moisture may help seedling to sustain and survive. In plain areas, line sowing is recommended. Germination of seed takes about a week time and newly emerged seedlings start growing. Young seedlings are very tender and needs proper care as these are likely to be suppressed by weeds and grasses. Development of tap root is very fast in *A. senegal* and once established it become hardy and resistant to drought. Direct seeding can be done by placing 5-8 seeds in 30 x 30 x 30 cm pits or larger or on field boundaries and rainwater harvesting structures, but plantation of nursery grown plants are generally used in dry areas. Mechanized seeding is not seen in India; however, it has been found successful on the clay plains in Sudan.

Artificial regeneration by nursery raised seedlings

Like any other acacias, raising of nursery does not pose any problem in *A. senegal*. The species can be easily grown by seed in nursery and after 6-8 months out planted in the field during monsoon season. Healthy seedlings of *A. senegal* can be raised by sowing seeds in poly-bags of 20x10 cm size. The most common potting mixture consisting of soil, sand and FYM in 1:1:1 ratio is used. For filling in root trainer containers, mixture consisting of sand and FYM in 20:80 ratio gives better results (Prasad *et al.,* 2002). Tray type root trainers having 250 cm^3 cell sizes are the best for raising plantable size seedlings. If seedlings are to be retained for an extended time in nursery to get long and sturdy seedlings, 500 cm^3 single cell root trainer pots are better suited. The development of plantations artificially involves seed collection, proper storage, pre-sowing seed treatment, nursery management planting seedling in the field and protection and maintenance of out planted saplings.

Seed collection

Generally, seeds are produced almost every year during December-April. Seed production is greatly influenced by the annual rainfall and age of the plant. Seed production is more profuse in 10 to 12-year-old plants. The ripe pods upon drying usually burst while still on the plant. The seeds fall on the ground and either blown away or buried. It is difficult to collect seeds fallen on the ground. For collection of healthy seeds, it is desirable to pick up mature pods before they get burst on drying. The pods are collected manually. They can also be collected by beating off the branches with stick and the fallen pods are collected. The pods can also be collected safely by clippers mounted on bamboo poles. The collected pods are sun dried for 6-8 days, and the seeds are then separated. Seed extraction may require light beating of the pods with sticks or mallets at times. Seeds can also be separated by trembling on pods wrapped in bags or by pressing pods between hands. Seeds are separated from chaff and other impurities by sieving and winnowing. Seeds need to be completely air dried and stored in air tight containers in cool and dry place. They can also be stored in tins. Freshly extracted seed should immediately be dusted with an insecticide. Seed will remain viable for 3-4 years if kept in opaque, air tight container (FAO, 1974). Seeds of *Acacia senegal* are orthodox and store well in a cool, dry, insect-free place. At 10°C and moisture content of 5-7%, the viability of seeds can be maintained for several years (Joker, 2000).

Pre-sowing treatment and seed germination

Seed of *Acacia senegal* is not impermeable to water even after storage, and scarification is normally not necessary. Seed can be sown immediately after collection (Joker, 2000). Fresh seed requires no pretreatment if sown immediately after harvest. However, it is desirable to give pre-sowing seed treatment to get not only rapid and uniform germination after sowing, but also to ensure high germination percentage. Soaking seed in water for 12-24 hours gives good results, however pretreatment in hot water for 10 minutes has also been observed beneficial (Sanyang *et al.*, 2008; Enyang *et al.,* 2020). Seed collected in previous seasons, requires pretreatment to break seed dormancy like mechanical and chemical scarification (Girase *et al.,* 2002). Seeds can also be nicked. More mature seeds can be immersed in concentrated H_2SO_4 for 3-15 minutes or dropped in boiling water for 5 seconds. After soaking in H_2SO_4, the seeds are removed from the acid and rinsed under running water.

Seed sowing in nursery

Sowing of pre-soaked and pre-germinated seed in nursery give high percentage of germination. Seeds collected from different localities shows considerable variation in germination capacity. A review by Alkali (2010) on silviculture of *Acacia senegal* outlined the normal nursery practices. The beginning of the nursery practice should be 3-4 months before the rainy season and should be started with the best quality seeds collected from mature plus trees of best growth and form, which produce the best quality gum. Sowing of 2-4 seeds per pot should be done in polythene pots filled with a 2:2:1 mixture of soil, sand, and composted manure with sufficient protection of the young seedling from direct sunlight.

For better results, seed should be sown in polypots or in 30 cm long tubes, 2-4 seeds per tube, thinned to one seedling after 4-6 weeks. Frequent root pruning is necessary in container plant as the tap root grows very fast. Planting out can take place after 4-6 months. Seedlings grown in organic potting mixtures develop fibrous root systems; effectively bind the media within the container, which is essential to minimize negative effects on plants during transporting or transplanting **(**Dalzell *et al.,* 1987; Miller and Jones, 1995**)**. Negative effects of compost on seedlings are very rare and if there are any they might come from weeds, disease and pest infestation and harmful polyphenols (Miller and Jones, 1995; Stofella and Kahn, 2001; Gonzalez and Cooperband, 2003). Positive effects of compost on seedling growth have been observed over the mineral soil poor in nutrients. Daldoum and Ameri (2013) prepared a compost mixture of forest litter and poultry manure in 4:1 ratio in a pit with a maturation period of three and a half months. Four growing media were prepared by mixing compost with silt soil (volume/volume) as follows: Silt + zero compost; Silt + 25% compost; Silt + 50% compost and Silt + 75% compost. The compost in comparison with the silt soil was slightly acidic, non-saline and rich in nutrients, and had a high water holding capacity. Though compost has negatively affected the germination capacity of the acacia seeds, but it positively stimulated growth of the seedlings and showed significant difference from silt medium. Root length growth in the compost media as compared to the silt medium was moderate, due to the relative richness of the silt soil in nutrients. Compost amendments had increased the biomass of the *A. senegal* seedlings as compared to silt soil.

Watering in nursery

Watering in nursery is the most crucial operation which decides quality of planting stock in the nursery and success or failure upon its transplanting in the field. Adequate and dependable supply of water is needed during nursery settings for optimum growth of the seedlings. Frequent watering in nursery is required till germination is complete. In first week when seed is germinating, light watering is done twice a day. After completion of germination, alternate day watering is sufficient for few weeks. Excess watering results in production of pampered seedlings which fail when planted out in harsh field conditions. Therefore, frequency of watering in nursery has to be planned most judiciously. The number of watering and quantity of water per plant or per bed depends on locality and the season. Isah *et al.* (2013) studied the effects of 4 different watering regimes (once daily, twice daily, once in 2 days and once in 3 days) on the growth of seedlings and found that watering of the seedlings once between two to three days was effective in the semi-arid region, though the responses varied among the provenances.

Shading in nursery

Young seedlings of *A. senegal* need to be protected from scorching heat in summer months and severe cold in winter. Net shade is the best way to protect seedlings from heat in summer and frost in winter. In absence of net shade, thatched shade of locally available materials (Munj-*Saccharum munja*, Kheep-*Leptadinia pyrotechnica,* Parali *etc.*) is the best way to protect seedlings from heat and frost. Proper shading of nursery increases germination (Goda, 1987) and enables seedlings to grow well.

Hardening of seedlings

Hardening of seedlings is a necessary process to prepare seedlings for planting in the field. In nursery seedlings are kept under constant care for their development. The good seedlings are selected and placed separately where they are given less watering and exposed to sun gradually to condition them for planting out in field. Normally one-month time is sufficient to harden and acclimatize seedlings to natural environment. Harden up seedling for 3-4 weeks before planting in the field become capable to bear the transplanting shock and establishes well when planted out hence, resulting in better success.

Size and quality of planting stock

Healthy and quality seedlings of *A. senegal* should be selected for transplanting in the field. Generally, seedlings attain 40-50 cm height in 3-4 months with a woody stem. Small and poor seedlings should be culled out in nursery. The seedlings with good quality parameters *viz.*, sturdiness, root-shoot ratio and Dickson quality index (DQI) should be used for transplanting in the field. Generally, 6 month-old seedlings attain good quality parameters for out planting (Plate 5). However, it would be desirable to plant 8-12 month-old seedlings of 75-100cm height if planting is to be done on difficult sites where facility of irrigation is not available and plantation is to be established during monsoon.

Plate 5. Quality planting stock of *A. senegal* in nursery

Artificial Regeneration by Vegetative Propagation

Propagation in *Acacia senegal* is achieved both by seeds planted in nursery and by vegetative means using cuttings, grafting, layering and micro-propagation (tissue culture). For vegetative propagation by cuttings, smaller and thinner cuttings or branch cutting are taken from the crown of mature trees (12-13 years old). In micro-propagation studies on axillary bud induction from nodal explants of field grown mature (10-20 years) trees of *A. senegal* have been found effective (Gupta *et al.*, 1994). The nodal explants are most suitable for multiple shoot formation (Kaur *et al.*, 1998; El-Tigani and Ali, 2001). A production protocol (Ali *et al.*, 2013) of *Acacia senegal* by *in vitro* micro-propagation techniques shows a great potentiality in shoot regeneration and rooting.

Planting

Planting of *Acacia senegal* is relatively less and it is grown primarily by seed sowing. However, in less rainfall zone where low soil moisture restricts germination of sown seeds, nursery grown seedlings are used to establish the plantations. To raise commercial plantation for higher gum production, quality planting stock should be planted at proper spacing depending on site conditions and type of plantation stands aimed. In monoculture on rocky and gravely site the seedlings are planted at 3x3m or 4x3m spacing. For silvi-pastoral system the seedlings are planted at 5x5m or 10x5m. In agri-silvi-cultural system the planting is done at 10x10m spacing. In arid region of western Rajasthan, agri-silvi-cultural system based on *A. senegal* (kumat) support good yield of crops like millet, beans and groundnut. The nursery raised quality size seedlings (~50 cm tall) are planted in July-August when monsoon sets in. The planting should be done in 30x30x30 cm or 45x30 cm size pit after filling them with compost and soil in 1:1 ratio. The plant should be watered at planting and again after one week if rain fails after planting. In good monsoon year, plants get established in six months and become hardy to sustain harsh climatic environment. However, for better success 1-2 watering are advised during summer in the first year of plantation. Strict protection from fire, livestock grazing and efficient control of weed competition during initial 2-3 years of plantation is important for survival and growth of saplings. Because of slow growth, initial annual increment in plant height is 30-40 cm (15-25 cm in Indian arid zone). Weeding is essential after planting and to be done 2-3 times in the first year and another 2 growing seasons. The young plants need protection from livestock for the first 3 years until they have grown out of their reach. Post planting care and pruning should be taken regularly from fourth year onwards for development of good stand and higher gum production.

For establishing *A. senegal* plantation on stress and/or relatively compact site, pit size of 60×60×60 cm is used. Also, sub-soiling to be done up to depth of 60-70 cm to loosen the soil and improve rainwater infiltration downwards. Under compact soils application of 150 g of NPK fertilizer per planting pit would assure faster growth in the first year and increases drought resistance of the planted seedlings. The rooting habits of *Acacia* species are especially suited to making maximum utilization of available moisture by both types of roots, *i.e.*, surface feeding/spreading roots to exploit available soil water and nutrients from the surface strata and the anchoring roots to support survival and growth during water stress period. Germinating seed develop a long tap root reaching about 2 m in two months, then growth of lateral roots develops in the second and third year. This branching and far rooting enables the young seedling to grow even after the rain has stopped (Alkali, 2010). The plants originating from direct sowing produces higher number of branches as compared to the planted ones (Raddad, 2018). Watering is important on early growth of *Acacia senegal*. Alternatively, micro-catchment rainwater harvesting structures (saucers of 1.5 m radius with 20% slope towards plant of V-ditches) can also be prepared to enhance growth of the plantation (Singh *et al.,* 2011). Omer *et al.* (2004) suggested that supplementary irrigation is beneficial for growth, especially when applied at intervals of 2 or 4 weeks.

In arid and semi-arid regions of India, particularly in Rajasthan, Gujarat, Haryana and Punjab, there is a good scope for extending large scale plantations of *A. senegal* by integration of it in agroforestry on farmlands. Recently, Bundelkhand region of central India has become a hot spot for agroforestry plantations of *A. senegal*. ICAR-Central Agroforestry Research Institute (CAFRI) Jhansi has developed different types of agroforestry models based on *A. senegal viz.* agri-horti-silviculture, agri-silviculture, single and double row-biofence model and block planting model for rocky/degraded site; and are being disseminated on farmers' fields and other sites. The bio-fence model so developed by ICAR-CAFRI has attracted many farmers for its adoption on their farmlands. Bundelkhand region represents typical semi-arid climate and offers great potential for extending area under plantation of *A. senegal*. In the last five years, ICAR-CAFRI has provided about one lakh quality planting material of *Acacia senegal* to farmers of Bundelkhand region (Figure 2).

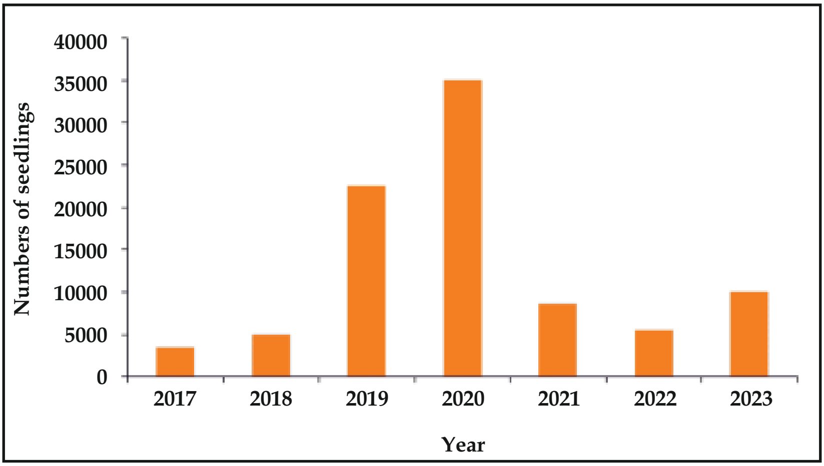


Figure 2. ***A. senegal*** **seedlings provided by ICAR-CAFRI to farmers of Bundelkhand**

Insect, Pest and Disease Management

Acacias contain organic compounds which act as natural repellents that defend or protect them against pests and grazing animals. The thorny nature is also a defense mechanism against browsing by animals. Some of the insect pests affecting trees in arid and semi-arid regions include termites, defoliators, sap suckers, seed and wood borer. The buffalo treehopper (*Stictocephala bubalus*) generally destroys the seed crops of *A. senegal*. Spiders (*Cyclops* sp.) can smother young growing tips, whereas the grub stages of beetles (*Coleoptera*-bruchids), and larval stages of moths damage the seeds. Locusts (*Acridium melanorhodon*) defoliate vast areas of *Acacia senegal* plantation overnight, whereas browsing goats and camels are major enemies to the plantation up to 4-5 years. Frequent pests cause defoliation and thus decrease the photosynthetic capability of *Acacia senegal* and in turn the quality of stored carbohydrates connected with a reduction of growth and gum yield. The most damaging longhorned beetles have been identified as *Crossotus subocellatus*- known from the southern part of the Arabian penninsula, Sudan, Djibouti (locality), Somalia, Ethiopia, Eritrea, Kenya. In northern Africa it is only known from Egypt, Libye, Sénégal, Maroco, Chad, Mauritanie, and Niger. *Titoceres jaspideus*- a common species throughout Africa, have been recorded from the most countries south of Sahara, from South Africa northward to Sudan, Chad, Niger, Western Sahara, Mauritania, Chad, Maroco, Namibie, Sénégal and

Somalie. The species *Crossotus albicollis* occurs in Senegal, Mali, Niger, Chad, République Centraficaine, Nigeria, Cameroon, Ghana, Côte d'Ivoire, Burkina Faso and Mauritania. The species *Coelodon servum* occurs in Senegal, South Africa, Namibia, East Africa (Ethiopia, Somalia, Kenya, Tanzania, *etc.*).

There are several constraints for growing *Acacia* sp. as tree component in agroforestry system. *Acacia senegal* is also attacked by the fungi *Cladosporium herbarium, Fusarium* sp., *Ravenelia acaciae-senegalae* and *R. acaciocola*. The fungal diseases like heart rot, root rot and basal stem rot caused by basidiomycetes fungi are the main among the different constraints. Manjunath *et al.* (2016) first time reported root rot disease caused by *Ganoderma* sp. in 7-years-old *Acacia senegal* planted as a tree component of agri-silvi-hortculture model of agroforestry at farm of ICAR-Central Agroforestry Research Institute (CAFRI), Jhansi. The wilting off of seven-year-old *Acacia* tree was observed during field visit in *Acacia* plantation due to fungus, *Ganoderma* sp. infection. The infected plant showed symptoms with wilting, stem blackening, defoliation (Plate 6a) and production of fruiting bodies (basidiocarps) at the base of the tree (Plate 6b). The corrective measures to reverse the process of drying the tree (trenching around the tree roots and application of Captan and Carbendazim fungicides) did not work. It took almost two months' time from first sign of wilting (mid July 2016) to complete death (mid-September 2016) of tree. Further, morphological characters of basidiocarp were recorded through visual and microscopic observations. The basidiocarps were 9–12 × 11-14.5 × 1.4 cm diameter in size, woody surface, sub sessile to laterally stipitate with 2-3.5 cm in length and kidney shaped. Upper surface was waxy shining, dark reddish, yellowish towards margin, brittle and soft. Slight margin blunt, rounded, brown white (Plate 6c). Pore surface creamish to milky. Cutis is light brown colour, thick walled claviform type (Plate 7a). Skeletal hyphae, brown colored, thick walled and aseptate (Plate 7b). Earlier, *Acacia* species such as *A. mangium, A. aulococarpa, A. auriculiformis* and *A. crassicarpa* have been reported to be attacked by *Ganoderma* sp. causing root rot disease. The findings of Manjunath *et al.* (2016) confirmed *Acacia senegal* as a new host for *Ganoderma* sp. and root rot cause by it can kill the trees.

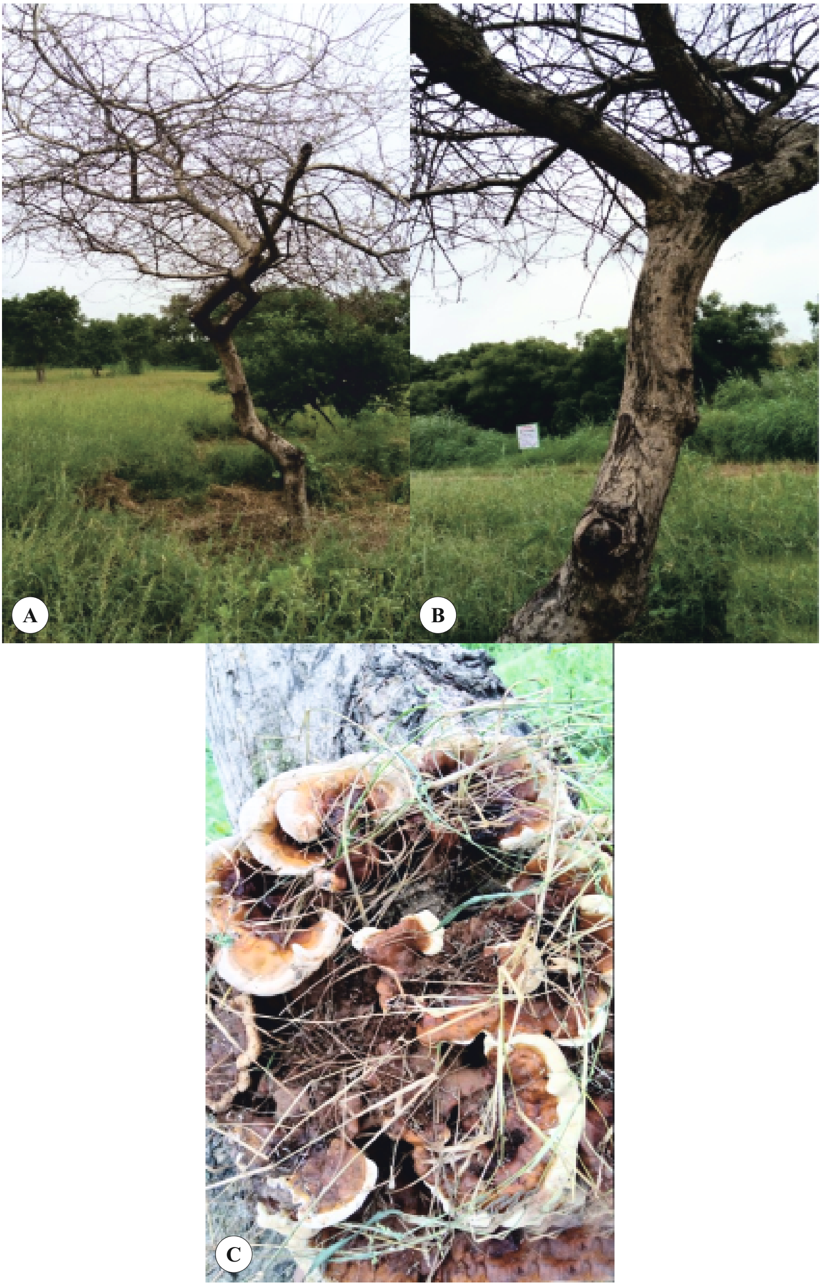
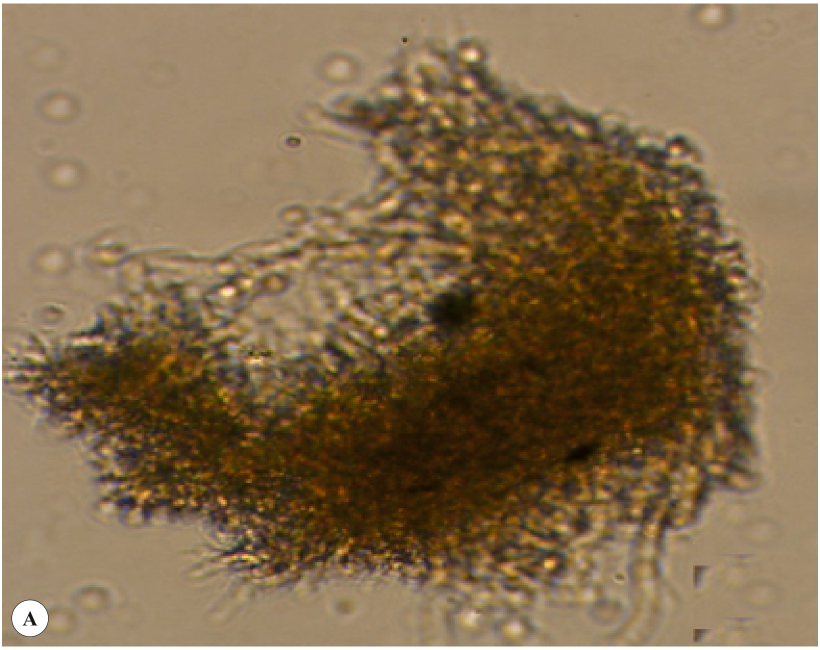


Plate 6: Symptoms of *Ganoderma* infected 7-year old tree of *A. senegal:* wilting, stem blackening, defoliation (A & B); fruiting bodies (basidiocarps) at the base of the tree (C)



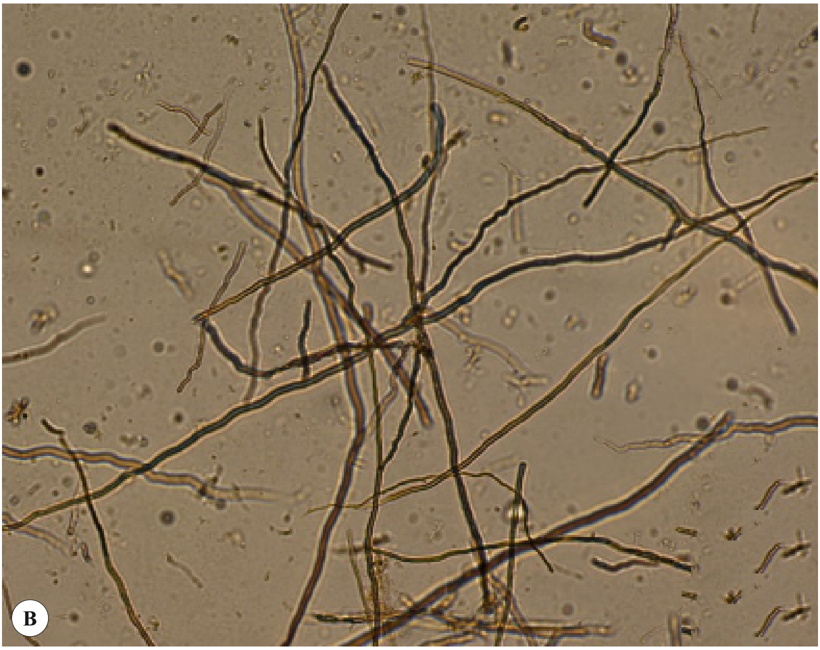


Plate 7. Basidiocarp morphological characters: light brown cutis, thick walled claviform type (A); brown skeletal hyphae, thick walled and aseptate (B)

Chapter 6 Tree Growth and Yield

African Drylands

Senegalia senegal or *Acacia senegal* trees are common in the savannas and drylands of Africa, Australia, India, and South and North America and are frequently planted in the Sahel region of Africa (Dreyfus and Dommergues, 1981). The natural *Acacia senegal* stands constitute one of the most important types of natural forests in Sudan, which occur in the gum arabic belt that lies within the low-rainfall savannah zone between latitudes 10°and 14°N (Vogt, 1995). It also supports dryland ecosystems in tropical Africa. It remains one of the most commercially exploited multipurpose agroforestry tree species (Fagg and Allison, 2004). It accumulates a large biomass when given sufficient water (Gaafar *et al.*, 2006). In Sudan, a traditional rotation with agricultural crops and *A. senegal* was established to maintain soil fertility (Ballal *et al.*, 2005) and has a low input production cycle (Raddad *et al.*, 2006). Despite its commercial, industrial, agricultural, and ecological importance, *Acacia senegal* tree still remains under-utilized in African drylands. Such under-utilization is attributed to a lack of knowledge of production systems. Nonetheless, *A. senegal* has been a successful crop in agroforestry systems in the Sudan and several West African nations. *Acacia senegal* shows considerable variation in its growth in different habitats, localities and sites. In nature, it acquires maximum growth in rainy season and growth may vary with quantum of rain received in different regions. Most of the scientific documentations from West African nations focus on gum production from trees in varying habitats and regions. Majority of the available tree growth data relates to tree-girth in relation to gum-tapping and yield. The information on systematic time series tree growth data of *A. senegal* from artificially raised plantations is meager.

El-Amin *et al.* (2015) studied woody biomass of *Acacia senegal* trees by applying allometric equations for ground data combined with satellite data sets in *Um Habila* Reserved Forest (2.7 square kilometres) located in El Rahad Locality in North Kordofan State, Sudan. The study findings revealed that the mean diameter of *Acacia senegal* tree was 7.31 cm±1.68 cm. The tree above ground biomass (TAGB), tree below ground biomass (TBGB) and total tree biomass (TTB) of *Acacia senegal* were found to be 15.15±9.01 kg, 3.03±1.80 kg, and 18.18±10.81 kg, respectively. They integrated remotely sensed data with the terrestrial method for creating and correlating the relationship between them and developed the power model based on spectral reflectance (IR) with adjusted R^2 of 0.504. They concluded that application of allometric equations is useful as non-destructive method for local biomass estimation and the application of remote sensing is recommended for biomass estimation in wide coverage areas.

Diatta *et al.* (2021) investigated the survival and growth of trees from 15 African *Acacia senegal* (*Senegalia senegal* (L.) Britton) provenances tested in two environments and related the differences among provenances to the climate at their site of origin and tree age. The study was based on 14 years growth in a common garden trial at two sites (Bambey and Dahra, Senegal) that differed in water availability and subsequent follow up by later assessment after 23 years at one of the sites. The findings revealed that the variation among provenances in survival, height, and diameter was significant, and differences could be partly explained by the climate at their site of origin. In general, provenances from dry sites survived better at both sites. The results support that divergent selection creates and maintains local adaptation of *Acacia senegal* provenances in relation to growth (height and diameter) and survival in areas with different water availability. This has important implications for choice of appropriate planting material for tree planting and for conservation of genetic variation among natural populations, but also for prediction of the effects of climate change.

Mohamed (2005) studied the suitability of *Acacia senegal* stands for agroforestry with regard to soil moisture depletion and physiological traits. In the first set of experiments, the effect of tree size on soil water depletion and on such tree characteristics as photosynthesis, stomatal conductance, leaf water potential, relative humidity and inter-cellular CO_2 concentration was examined. The physiological behavior of *A. senegal* was assessed to elucidate its drought adaptation mechanisms. In the second set of experiments the effect of the density of a planted *A. senegal* stand on two traditional food and cash crops, sorghum and karkadeh, was evaluated to determine the interaction between trees and field crops, using gum and agricultural crop yields and physiological characteristics as criteria. The study was conducted during two rainy seasons in the Domokeya reserve forest near El Obeid town in western Sudan. Soil moisture was measured initially with a theta probe and subsequently with a neutron probe from different soil strata to the depth of 250 cm. A portable photosynthesis system was used for measuring, in trees as well as in field crops, the photosynthesis rate, stomatal conductance, relative humidity and inter-cellular CO_2 concentration. The leaf water potential was measured with a pressure chamber. The results indicated that as the tree size increases the amount of water depleted from the soil profile also increases. Significant positive correlation was found between the amount of water in the profile and the tree photosynthetic rate. The data indicated that water uptake by trees of different sizes came mostly from the 0-150 cm soil layer, with less uptake from deeper layers (Table 1). The morning leaf water potential and stomatal conductance in trees were significantly affected by tree size. Gum production and tree physiological traits were found to be highly responsive to changes in soil water. It was concluded that *A. senegal* is capable of physiological adjustment in response to soil moisture as a form of ecological adaptation. All measured traits in trees were significantly affected by tree density and by the presence of agricultural crops. There was little evidence of complementarity in resource sharing between trees and crops, since both trees and field crops competed for soil water from the same soil depth. This was the most important interaction noticed between trees and crops. Gum yield increased when sorghum was intercropped with trees, and the per-tree and per-area gum yields were higher when the density of trees was higher. With intercropping of karkadeh, the gum yield showed an increasing trend at a low tree density and a decreasing one at a high tree density, but these effects were not statistically significant. This, however, supported the finding that gum production depends on the soil water status. In both field crops, when grown in an agroforestry system, the yield was higher with a lower density of trees but did not reach the yield level obtained in pure-culture. This effect seemed to depend on soil water availability. Overall, *A. senegal*, when planted at 266 trees ha^{-1}, reduced the karkadeh flower yield by about 26% and its biomass by 37%, and the sorghum grain yield by 19% and biomass by 9%. Planting of 433 trees ha^{-1} reduced the karkadeh yield by 55% and biomass by 57%, and the sorghum grain yield by 44% and biomass by 45%, relative to sole crops. This variation seemed to be caused by the influence of intercropping design on soil water. *A. senegal* agroforestry system seemed to have a higher rain use efficiency as compared to pure tree stands or crops. Intercropping design significantly affected the soil water status, photosynthesis, stomatal conductance and leaf water potential both in trees and in crops. Karkadeh appears to be more appropriate for intercropping with *A. senegal* than sorghum and particularly recommendable in combination with a low tree density. Overall, it was concluded that, in *A. senegal* agroforestry, tree density affects the competition for soil water between agroforestry system components. Modification of tree density can be used as management tool to mitigate competitive interaction in the intercropping system. Five-year data on provenances study that included a selection of seed lots from the Sahel (Burkina Faso, Niger, Mali and Sudan) and one provenance from Rajasthan in India (Raebild *et al.,* 2003) indicated significant differences for all characters except number of stems. The provenance from India had a very poor performance. Provenances from the Sahelian phytogeographical zone had a faster height growth than the two provenances from the Sudanian zone. The best provenance had a dry weight production of approximately 1.4 t ha^{-1} y^{-1} ranging from 0.13 t ha^{-1} for Rajasthan 03 to 6.8 t ha^{-1} for Niger 1 (Raebild *et al.*, 2003). A wide variation in provenance differences in water use efficiency, biological nitrogen fixation, photosynthesis, biomass and gum arabic production have also been observed in *A. senegal*, where gum yield declines with increasing water use efficiency of the stand (Gray *et al.,* 2013).

Table 1. Effect of *A. senegal* tree size on the amount of water (mm) in soil layers (Mohamed, 2005)

Tree size class	Amount of soil water (mm)			Per-tree gum production (g)
	0-75 cm	0-150 cm	0-250 cm	
>5 cm	23.97	53.22	82.19	409.5
5-10 cm	23.14	50.01	74.88	366.1
10-15 cm	19.97	44.83	69.30	433.4
15-20 cm	18.69	44.62	73.81	335.8
20-25 cm	19.81	44.42	72.08	284.7

By recording growth data of 489 number of trees of *Acacia senegal*, Diello *et al.* (2013) calculated the mean age as 9.14 years with minimum and maximum stem diameters at breast height (dbh) as 0.0 and 210.00 cm, respectively (mean of 64.48 cm). The stem basal diameter varied from a minimum of 10.00 cm to a maximum of 103.00 cm with a mean of 36.73 cm. The crown diameter varied from a minimum of 0.95 m to a maximum of 7.85 m with a mean of 3.56 m. The result also revealed positive and significant correlations between dbh, stem basal diameter, crown diameter, crown depth and tree height, crown depth and crown diameter. Based on the study these authors gave a model to estimate the age of *Acacia senegal* trees as: Age (years) = −35.8 − 0.05 SBD + 0.01DBH + 0.17 $HBFR^{0.04}$ + 1.33 $CD^{0.46}$ (Diello *et al.*, 2013). Here, SBH is stem basal area, DBH is diameter at breast height (cm), HBFR is height (m) from the base to the first ramification, and CD is crown diameter (m). Biomass accumulation curve for dry forest observed by fitting six data points taken from two studies of secondary forest and assuming a maximum rate of biomass accumulation at year 60 indicated that *Acacia senegal* produce maximum biomass of about 60 tons dry matter per ha (Winrock International, 2013). Ndathi (1994) studied the primary production and standing biomass of *Acacia reficiens* and *A. senegal* on the mountain slopes and lowlands, where the lowlands supported 10.52 tons ha^{-1} biomass, in which contribution of *A. reficiens* and *A. senegal* were 9.31 tons ha^{-1} and 1.22 tons ha^{-1}, respectively. The mountain slopes supported 6.34 tons ha^{-1} from *A. senegal* plants. *A. reficiens* on the lowlands produced 0.38 tons ha^{-1} and 0.11 tons ha^{-1} of leaf and pod biomass on annual basis, while *A. senegal* produced 0.04 tons ha^{-1} and 0.02 tons ha^{-1} of leaf and pod biomass respectively. The leaf and pod biomass production from *A. senegal* on the mountain slopes was 0.15 tons ha^{-1} and 0.06 tons ha^{-1}, respectively. This indicates that biomass accumulation of *A. senegal* is relatively higher on hillslopes particularly when available along a dry drainage line.

Based on a total of 5774 tree heights and corresponding diameters at breast heights measurements, Osman *et al.* (2013) modeled height-diameter relationships of *Acacia senegal, Acacia seyal, Anogeissus leocarpus, Balanites aegyptiaca,* and *Combretum hartmannianum* and described height-diameter relationship by non-linear models. Out of the evaluated models, at least 15 models were found to give reasonable results for each species with R^2 ranged from 0.73 – 0.89 and RMSE of 0.5 – 0.9 m and can be useful at local stand level or best in similar biological and stand structure conditions. *Acacia senegal* also sequesters atmospheric carbon in its biomass as well as under canopy soils and thus helps mitigate climate change. Study on mean tree biomass and soil carbon (C) densities of *Acacia* woodland in savannah region indicated aboveground biomass C and soil organic carbon (SOC) densities at 112 and 5453 g C m^{-2}, respectively. Belowground biomass C densities, estimated using root shoot ratios was 33 g C m^{-2}. Both aboveground biomass C and SOC densities were correlated with mean annual precipitation. In a study carried out during 2008-09 in Surendranagar in Gujarat and Dungarpur, Jhunjhunu and Pali districts of Rajasthan for the *Acacia senegal* forest (6/E2, Champion and Seth,

1968) indicated average carbon density of 12.93±5.46 tons ha^{-1} in 0-30 cm soil layer (Singh, 2009).

Considering gum arabic-producing *Acacia senegal* tree as the most important component of traditional dryland agroforestry systems in the Sudan, Raddad *et al.* (2006) investigated whether the spatial arrangement of trees and the type of agricultural crop intercropped, influence the interaction between trees and crops. Tree and crop growth, gum and crop yields and nutrient cycling were investigated over a period of 4 years. Trees were grown at 5 x 5 m and 10 x 10 m spacing alone or in mixtures with sorghum or sesame. The findings revealed that no statistically significant differences in sorghum or sesame yields between the intercropping and control treatments were observed (mean values were 1.54 and 1.54 t ha^{-1} for sorghum grain and 0.36 and 0.42 t ha^{-1} for sesame seed in the mixed and mono-crop plots, respectively). At an early stage of agroforestry system management, *A. senegal* had no detrimental effect on crop yield; however, the pattern of resource capture by trees and crops may change as the system matures. A significant positive relationship existed between the second gum picking and the total gum yield. The second gum picking seems to be a decisive factor in gum production and could be used as an indicator for the prediction of the total gum yield. Soil organic carbon (OC), N, P and K contents were not increased by agroforestry as compared to the initial levels. Soil OC was not increased by agroforestry as compared to sole cropping. There was no evidence that P increased in the topsoil as the agroforestry plantations aged. At a stocking density of 400 trees ha^{-1} (5 x 5 m spacing), *A. senegal* accumulated in its biomass a total of 18.0, 1.21, 7.8 and 972 kg ha^{-1} of N, P, K and OC, respectively. Agroforestry contributed approximately 217 and 1500 kg ha^{-1} of K and OC, respectively, to the top 25-cm of soil during the first four years of intercropping.

Alemu *et al.* (2013) evaluated the gum arabic yield from natural stands of *A. senegal* and the growth of 6 provenances in different parts of the Ethiopia. For the gum yield evaluation from natural stands, four tapping positions and three tapping seasons were tested in a factorial RCB design. The second experiment in Metema evaluated survival and growth of six provenances. *A. senegal* trees in natural stands respond well to tapping if tapped during the appropriate season and at the correct position on the tree. The mean gum yield did not vary significantly by tapping season (p=0.63). Higher mean yield was, however, collected from trees tapped in October (96 g·tree^{-1} per two harvests). The mean yield differed significantly (p=0.009) between the tapping positions. Mean separation (α=0.05) shows that trees tapped at mid stem gave higher yield (160 g·tree^{-1} per two harvests). The interaction effect of tapping season and position was not significant. Higher mean yield ((70 ± 112) g·tree^{-1}) was recorded in mid October-mid stem in two harvests. The second experiment indicated statistically significant difference in mean survival (p=0.0298), height (p=0.000) and root collar diameter (RCD), (p=0.012) between the six provenances. Highest survival, height and root collar diameter growth was observed from Abderafi provenance (100%, (148±11) cm, (38±11) mm, respectively). They recommended October and mid-stem and branches as appropriate tapping season and position. Further, they recommended planting of the Abderafi provenance for the study area due to its superior growth and survival. The study contributes to the proper selection of provenances for plantation development and improved tapping technology for better production of gum arabic in Ethiopia.

Harmand *et al.* (2012) evaluated effects of climate, soil, tapping date and tree provenance on gum arabic production in *Acacia senegal* plantations in the Sudanian zone of Cameroon where annual rainfall ranges from 650 to 1,250 mm. The tree plantations were established between 1985 and 1989, and the tapping tests were carried out between 1993 and 1998. Generally good adaptation and growth of the species were observed in the different site conditions of the study area. To optimize gum production, the best time to tap the trees was at the beginning of the dry season, when the relative humidity dropped. Depending on the location along the climatic gradient, the optimum tapping date varied from October 10th (650 mm isohyet) to November 25th (1,250 mm isohyet). At 650 to 800 mm annual rainfall, the average gum production per site varied from 100 to 500 g per tapped tree, corresponding to 50-250 kg ha^{-1} with a density of 500 trees ha^{-1}. However, in sites with annual rainfall higher than 1,000 mm, the gum production was generally lower and uncertain. Although the mean production on the different types of soil did not differ significantly when years were combined, the annual production was more variable and more dependent on climatic variations on sandy soils than on clay soils. The local Cameroon Laf provenance was more productive than foreign Sahelian (Senegal, Sudan) or Indian provenances. First observations and analyses of gum samples from the local provenance showed an outstanding brightness and classical properties typical of *A. senegal* exudates in the Sahel region. The study further revealed that on sandy ferruginous soils, annual gum production was more variable than on clay soils as the soil water content was more related to climatic variations on sandy soils. Nevertheless, on a multiannual scale, the levels of production were comparable for both types of soils. Therefore, numerous locations can be suitable for productive *A. senegal* plantations in Northern Cameroon, provided that soils dry out and trees can defoliate early in the dry season. The local provenance of *A. senegal* was the most productive and should be preferred for plantation. This confirmed the hypothesis that Sahelian provenances may require a dryer environment for high gum production. Conversely, it showed that gum exudation is not limited to provenances adapted to extreme aridity. These results on gum production in various pedoclimatic situations pave the way for an in-depth research on the ecophysiological drivers of gum arabic exudation by *A. senegal*. The longevity and gum production capacity in the long term of *A. senegal* stands still have to be assessed in different contrasting climate/soil conditions. In perspective, one way to alleviate insufficient water stress in sub-humid areas could be the use of compounds susceptible to have an effect on gummosis and gum exudation, such as Ethephon (2-chloroethylphosphoric acid), which releases ethylene and mimics the physiological stress believed to trigger gummosis.

Indian Drylands

In spite of multiple uses and wide occurrence of *A. senegal* in arid and semi-arid regions, it remains a species of low profile as far as raising plantations and monitoring tree growth is concerned in Indian scenario. It is only in recent past that the species has attracted attention of ecologists, foresters and other academicians due to threat of declining international trade of gum arabic as a consequence of overexploitation of existing and continuously dwindling natural production base.

For the growth of *A. senegal* in arid western Rajasthan, Harsh *et al.* (2003) reported that the tree growth correlate with edaphic condition of the site being maximum at sandy site followed by semi-rocky while minimum at rocky site (Table 2). Further, the high standard deviation and coefficient of variation in data indicated that tree growth was inconsistent and not uniform at different sites. Mertia *et al.* (2007) screened seeds of genetically superior five provenances of *Acacia senegal* from African countries procured from Centre Technique Forestier Tropical Laboratier (CTFT), France to identify a superior genotype for higher production of gum arabic in India. The seed raised seedlings were planted and evaluated for growth performance and gum production. The findings revealed that provenance from Nigeria was identified as superior in establishment, higher survival, fast growth performance and gum production (Table 3). At the age of 12 years the provenance from Nigeria attained tree height of 277cm with a CD (critical difference) of 7.2 cm and crown of 336 cm^2. After 12 years the gum yield ranged from 230 to 360g $plant^{-1}$.

Table 2. Growth of 34-years-old *A. senegal* (Harsh *et al.*, 2003)

Edaphic site	Tree height (cm)			Tree diameter (cm)		
	Range	Average	SD	Range	Average	SD
Sandy site	360-680	480.6	68.1	9.6-24.0	13.9	2.89
Semi-rocky	260-570	436.2	66.8	8.4-18.2	12.5	2.26
Rocky	180-540	337.4	68.4	6.2-19.4	11.7	2.87

Table 3. Growth performance and gum yield of *A. senegal* (Mertia *et al.*, 2007)

Age (years)	Height (cm)	Crown (cm^2)	Collar diameter (mm)	Gum yield (g $plant^{-1}$)	Number of gum tears $plant^{-1}$
Initial	40	-	3.7	-	
4	145	163	38.4	45 to 177	4-to 15
8	244	282	58.5	155 to 295	6 to 17
12	277	336	72.2	230 to 360	5 to 21

Studies conducted to evaluate growth and performance of *A. senegal* along with other species for stabilization of sand dune in western Rajasthan (1996 -2001) at Arid forest Research Institute, Jodhpur indicated that *Acacia senegal* grows well when planted in association with *Cassia angustifolia*. The mean annual increment in plant height of *A. senegal* was 19.1 cm per year. Under shelterbelt plantation, *A. senegal* attained a height of about 80 cm in 4 years in the sandy plain area of Bikaner, Rajasthan. (Anon, 2000). Singh *et al*. (2020) reported that in traditional agroforestry system in western Rajasthan, the height and diameter at breast height (DBH) of scattered *A. senegal* trees ranges between 3.5 -11.1 m, and 7.0 - 45.6 cm respectively. Arya *et al*. (2006) studied the performance of various plant species on rainwater harvesting structures (RWH) under frost prone arid conditions in India, where crescent shaped trenches (CST, 180 cm × 30 cm × 30 cm), trench with mound (TWM, 45 cm × 30 cm cross section area) and a control were the RWH treatments. The *A. senegal* trees attained a height of 151 cm, 183 cm and 203 cm in the control, CST and TWM, respectively at the age of 54 months indicating good response of *A. senegal* to RWH. In another study, *A.*

Table 4. Growth and dry biomass production of *A. senegal* (Singh *et al*., 2011)

S.No.	Growth variable (cm)			Dry biomass (g tree^{-1})				Root (g tree^{-1})	Total biomass (g tree^{-1})
	GBH	Height	Crown	Stem	Twig	Leaf	Total		
1	17.0	219.0	159.8	1055.0	1383.0	192.0	2630.0	820.0	3450.0
2	19.0	320.0	126.0	1826.0	1245.0	268.9	3339.9	2880.0	4327.6
3	19.0	378.0	176.8	1143.0	1151.0	215.8	2509.8	853.6	3363.4
4	20.0	320.0	134.0	2631.5	1460.6	321.9	4413.9	1433.4	5494.7
5	22.6	250.0	159.5	2854.0	1654.3	426.4	4934.6	36202.3	6555.1
6	24.0	430.0	160.0	3121.0	1867.0	378.6	5366.6	13652.6	6858.2
7	34.0	760.0	275.0	4657.3	3124.5	583.3	8365.0	29718.9	11218.4

senegal along with *Acacia catechu* sown along V-ditches or field bunds prepared for soil and water conservation and the bunds along the ditch prepared for protection measures performs better as compared to the seedlings planted after nursery raising (Singh, 2009). All the species of acacia like *A. catechu*, *A. ferruginea*, *A. leucophloea*, *A. nilotica* and *A. senegal* perform well with V-ditch rainwater harvesting structure as compared to other structures (Singh *et al.*, 2011). Growth and biomass study of *A. senegal* carried out during 2009-2012 for the girth class of 17.0 to 34.0 cm indicated significant relationship of tree girth with height (r=0.918, P<0.01), dry aboveground biomass (r=0.970, P<0.001), root (r=0.980, P<0.001) stem (r=0.937, P<0.01), twig (r=0.975, P<0.001) and leave biomass (r=0.948, P<0.01) (Table 4).

In general, growth and productivity of gum arabic trees remains low in desert and arid region spreading over Rajasthan, Gujarat, Haryana and Punjab states due to harsh climatic conditions characterized by high temperature, low and erratic rainfall, and high evapo-transpiration. However, in semi-arid Bundelkhand region of central India, Prasad *et al*. (2019a) reported that 8-year-old *A. senegal* had attained 22.3cm girth and 4.7m height in rocky hill, and performed better than arid region of western Rajasthan wherein after 12 years of age plants reported to attain height of about 3.0m on rocky and gravely soil (Mertia *et al.*, 2007). In agri-hort-silviculture system *Acacia senegal* attained height and girth of 4.6m and 28.8cm respectively, after 7 years of planting in Jhansi, the heart of Bundelkhand region (Prasad *et al.*, 2018a). At ICAR-CAFRI, studies on comparative growth of *A. senegal* planted on research farm and on farmers' field revealed that in general growth was better on farm than on farmers' field in Bundelkhand region (Figure 3).

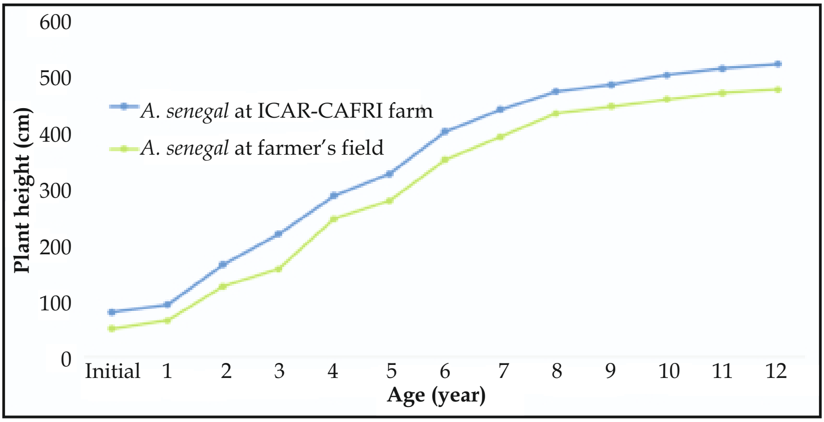


Figure 3. Growth of *A. senegal* on research farm and farmers' field in Bundelkhand

Chapter 7

Acacia senegal based Agroforestry Systems

Several global studies have indicated that India is vulnerable to climate change and likely to suffer with damages to agriculture, food and water security, human health and cattle populations. The realization and understanding of climate change is pre-requisite to take appropriate mitigation and adaptation initiatives at local level (Prasad *et al.,* 2012). Local communities have been coping with environmental change since millennia and have considerable knowledge about environmental change and means to cope up with its consequences (Salick and Byg, 2007). Agroforestry land use incontrovertibly has been used as low carbon climate smart agricultural technology since it embraces trees into farming systems for producing various marketable food and non-food products besides offering great potential of sequestering atmospheric carbon, and an almost zero cost approach for restoration of badly degraded land through nitrogen-fixing trees and shrubs. The introduction of trees reduce yield of those crops with which they are in direct competition for light, water and nutrients. The reduction in the yield is compensated by the tree products (fodder, wood, fuel, fruits, nuts, resins, gums, extractives, medicines, etc) which have much greater market values than the lost yield, so overall the system is economically more beneficial. Further, the benefits to soil fertility, soil structure, water infiltration, and the agro-ecosystem outweigh the losses of yield. Agroforestry systems achieve the goals of conservation agriculture, low carbon agriculture or climate smart agriculture by harvesting the solar energy in different strata, efficient utilization of horizontal and vertical space (both above & below ground), enhancing and balancing nutrients through recycling & pumping, and minimal soil disturbance (Prasad *et al.*, 2014a; Prasad *et al.*, 2023).

Agroforestry has been widely promoted in tropical countries. In India, the estimated area under agroforestry is about 28.4 million ha (Arunachalam *et al.*, 2022) which is likely to increase substantially in the near future. There are many gum-yielding tree species which can be planted as woody components along with crops in agroforestry. The associated crops and trees can vary from region to region and such agroforestry models will be highly beneficial to the resource poor farmers in providing livelihood security. The agroforestry models can be developed by planting selected tree species for the given agro-climatic condition. Trees can be planted on boundary of the field or as rows inside the field. The distance between row to row and tree to tree in a row depends on growth behaviour of tree species and associated crops. Generally, row to row distance should be such that agricultural operations can be performed without any hindrance. To reduce harm full effects of trees on associated crops, tree pruning must be conducted. The associated crops should be selected on the basis of selected tree species and its growth behaviour so that both components (woody perennial and annual crop) offer minimum competition to each other (Prasad *et al.*, 2018b). For development of gum and resin based agroforestry models, selection of tree species which produce gums and resins, is the first requisite. The tree species identified for different climatic regions are given below:

i. *Arid and semi-arid: A. nilotica, A. catechu, A. senegal, A. latifolia, Bauhinia retusa, Bombax ceiba, B. serrata, B. monosperma, Commiphora mukul, S. robusta* and *S. urens.*

ii. *Sub humid: A. catechu, B. ceiba, Canarium stritum, Dipterocarpus turpinatus, Garcinia morella, Hopea odorata* and *S. robusta.*

iii. *Humid tropics: B. ceiba, C. stritum, Cochlospermum religiosum, D. turpinatus, G. morella, H. odorata, Kingiodendron pinnatum, L. coromandelica, P. wallichiana, S. urens* and *Veteria indica.*

iv. *Sub-tropical: A. nilotica, A. catechu, A. senegal, A. latifolia, Bauhinia retusa, B. ceiba, B. serrata, B. monosperma, C. religiosum, C. mukul, G. morella, H. odorata, K. pinnatum, L. coromandelica, P. roxburghii* and *S. urens.*

v. *Temperate: B. monosperma, D. turpinatus, G. morella, K. pinnatum, P. roxburghii* and *V. Indica.*

vi. *Moist region: D. turpinatus, K. pinnatum, P. roxburghii, P. wallichiana* and *V. indica.*

Integration of *A. senegal* on Farmland

In arid and semi-arid region of India, *A. senegal* always remains the favorite gum-yielding tree to be integrated on farmland in the farm of agroforestry. Prasad *et al.* (2019b) opined that integration of gum/resin-yielding trees in agroforestry systems offer great potential for utilization of available resources and increasing productivity of natural resin and gums on sustainable basis besides providing livelihood support options and ensuring ecological stability of the land use. Omokhafe (2019) while highlighting the climatic concerns of Sahel region of Wet Africa in terms of desertification, loss of arable land, poverty, starvation, low productivity, low tree population, migration, child labor, human trafficking etc. opined that gum arabic based agroforestry model developed and recommended by Rubber Research Institute of Nigeria is in line with the FAO climate smart agriculture. They further reported that the potential for use of gum arabic tree in climate smart agriculture will provide carbon sink for climate change mitigation, which is a major concern world-wide. Besides, it will be beneficial in checking desertification, minimizing poverty among indigenous populations, and encouraging growth of the indigenous communities through gum arabic agribusiness from field to factory activities.

Mohamed (2005) opined that agroforestry systems based on *Acacia senegal* can, apart from their environmental benefits, also make full use of the available resources and thus lead to a higher combined yield as compared to growing trees or agricultural crops alone. Based on the findings, it was summarized that the gum yield can be significantly increased when the trees are inter-planted with agricultural crops, such as sorghum or karkadeh. The economic yield of these field crops is lower in combination with *A. senegal* than in pure culture; however, agricultural crop yields in gum gardens compare well with the average farm production level in Kordofan. A decrease in crop yield that results from competition between trees and crops can be tolerated, if the economic gain from gum production can be assumed to compensate for any loss in crop yield. It further revealed that North Kordofan State holds a considerable agricultural potential, despite land vulnerability, adverse climatic factors and poverty if farming is done based on *Acacia senegal* agroforestry. In an agroforestry system based on *A. senegal*, it is vital to select an appropriate tree density, so as to minimize the effect of root competition and to reduce the trade-offs between crop and tree productivity. Below-ground competition is inevitable when the root systems of trees and crops are likely to have similar distribution in the topsoil.

Agroforestry Models for semi-arid Bundelkhand

Bundelkhand is situated in north-central part of India and lies between the Indo-Gangetic Plain to the north and the Vindhya Range to the south. It is a gently sloping upland, distinguished by barren hilly terrain with sparse vegetation, although it was historically forested. Administratively, it comprises of 7 districts of Madhya Pradesh (Chhatarpur, Damoh, Datia, Niwari, Panna, Sagar and Tikamgarh) and 7 districts of Uttar Pradesh (Banda, Chitrakoot, Hamirpur, Jalaun, Jhansi, Lalitpur and Mahoba). The region shares a common culture.

The region experiences semi-arid, sub-tropical climate with rainfall ranging from 848-1197 mm. The region, geologically, is situated on hard granite rock. East southern part of Bundelkhand receives higher rainfall than West- northern part. By and large, terrain is undulating with exposed rocks at places. About 56% soil of the region is coarse textured red, while 44% is light black. Area along river Yamuna, which constitutes northern boundary is ravenous. The region suffers from water scarcity. Main source of irrigation in the region are shallow dug wells and dugout ponds or lakes. Perched water is tapped for irrigation and drinking. Agriculture is main stay of region's economy and well supported by dairying. Crop productivity due to various edapho-climatic conditions is low. Forests in the region are dry deciduous thorn forests which are rapidly degrading due to enormous pressure of extraction and slow regeneration. About 80% of total rainfall is received during southwest monsoon. The potential evapo-transpiration is quite high in the range of 1400-1700 mm with moisture index value of -40 to -50. The pattern of the rainfall is erratic and more than 90% of the total rainfall occurs within 10 weeks between July to mid September accompanied by intermittent long dry spells. The entire rainfall is received in less than 50 rainy days. Winter showers are rare and uncertain. The frequent drought occurs in entire regions. Usually, monsoon commences by the last week of June but sometimes delayed to the first week of July. The active monsoon often withdraws up to the mid of September or the end of August. Mean annual temperature is generally high with high degree of variation between minimum (5.8^{O}C in January) and maximum (39.8^{O}C in June) temperatures. Sometimes maximum temperature in the summer months of May and June touches 48^{O}C, which is the peak of summer season.

In semi-arid region Bundelkhand, there is a good scope for extending area for large-scale plantation of gum arabic. Ruthless overexploitation of existing resources led to decline in the domestic production and trade of gum arabic in India. To increase the production of gum arabic in typical semi-arid region of Bundelkhand in Central India, ICAR-Central Agroforestry Research Institute (CAFRI), Jhansi, which is one of the centres in the network project on harvesting processing and value addition of natural resin and gums took research initiatives in the year 2008 to introduce and integrate *Acacia senegal* on farm land in the form of agroforestry plantations. Some of the agroforestry models developed by ICAR-CAFRI are described below:

Multi-component agri-horti-silviculture model

This multi-components agri-horti-silviculture model, comprising of *A. senegal* and fruit-yielding plant species (*A. marmelos*, *C. limon* and *C. carandas*) was established at central research farm of ICAR-CAFRI, Jhansi in July, 2009. The aim was to develop model which is economically viable, climate resilient and suitable for adoption by small holder farmers. The total area of this smallholding farm is 72 m (width) and 68 m (length), wherein 28 plants of *A. senegal*, 28 plants of *A. marmelos* (var. CISH B1 and CISH B2) and 24 plants of *C. limon* (var. kagzi) were planted in rows. Row to row distance of *A. senegal* and *A. marmelos* was 20 m and in a row, plant to plant distance was 10 m. In every row of *A. senegal*, *C. limon* was planted at 10 m apart (one *C. limon* plant between two *A. senegal*). Thus, the model consists of eight rows, wherein first row comprises of *A. senegal* and *C. limon* placed at 5 m distance from each other (thus, 13 trees in a row), which is being alternated with *A. marmelos* row, planted at 10 m distance from each other (thus, 7 trees in a row). Along three sides of field bunds, *C. carandas* was planted (Figure 4). Intercropping in this model commenced from 2009 and continued thereafter. The cropping sequence of *P. mungo* or *V. radiata– L. culinaris or B. campestris or T. aestivum* was adopted for summer-winter seasons. For crop cultivation, standard package of practices have been followed. Out of five components *viz*., intercrops, *A. senegal*, *A. marmelos*, *C. limon* and *C. carandas*, four are woody perennials and are likely to compensate the losses due to failure of intercrops in the events of abnormal monsoon rain or extreme weather conditions.

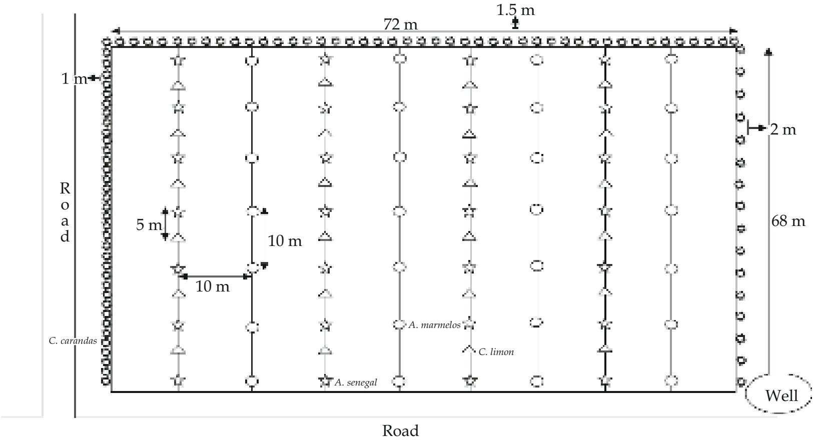


Figure 4. Design/layout of *A. senegal* based multi-component agri-horti-silviculture model

After 12 year of planting growth of different woody components of the model is given in Table 5. *Acacia senegal* started gum exudation after five years, while fruiting in *A. marmelos* was noticed after 6 years. The *C. limon* and *C. carandas* started fruiting at the age of three years (Plate 8 A, B, C, D & E).

Table 5. Growth of woody plants in *A. senegal* based multi-component agri-horti-silviculture model

Woody Component	GBH (cm)	Height (m)	Canopy spread (m^2)
A. senegal	46.5	6.0	25.3
C. limon	24.1	4.3	16.2
A. marmelos	57.3	6.1	36.8
C. carandas	4.4	2.1	2.3

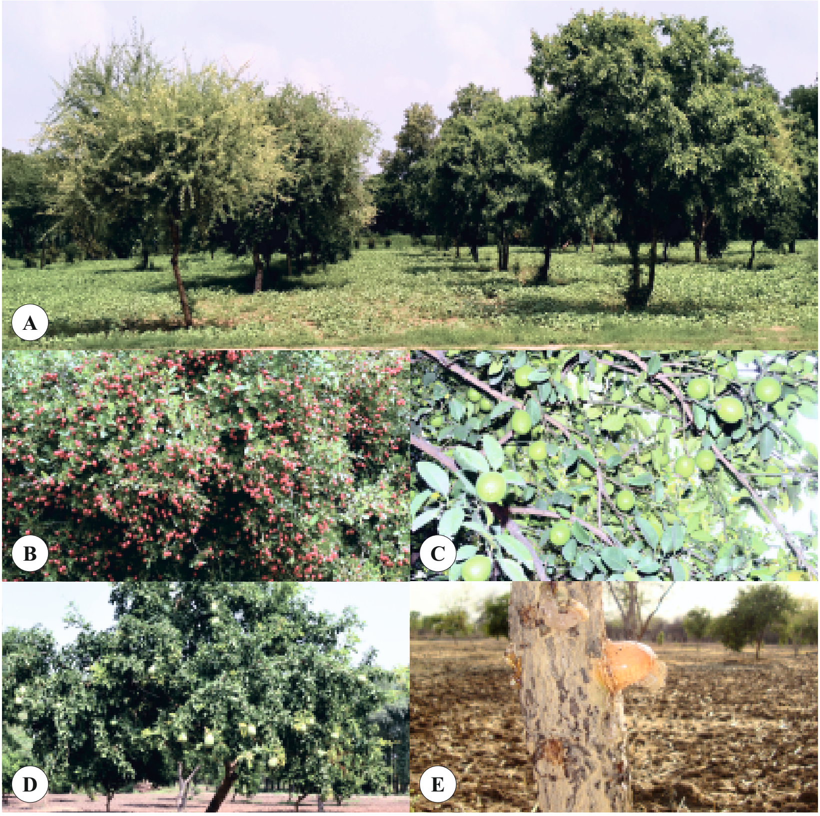


Plate 8. ***A. senegal*** **based multi-component agri-horti-silviculture model (A), fruiting in karonda (B), Lemon (C), Bael (D) and exudation of gum arabic (E)**

Prasad *et al*. (2018a) studied the performance of winter season intercrops in multi-components agri-horti-silviculture model. In winter season, *B. campestris* (var. Varuna) was taken as understory crop during 2012-13 & 2013-14 and *T. aestivum* (var. HUW 234 Z-1) during 2014-15 & 2015-16. After preparing field, seeds were sown and all recommended package of practices were followed for both the crops. The findings revealed that the different woody species of the model exhibited different impacts on growth and yield of understory crops. Among woody species, *A. marmelos* exhibited comparatively lesser negative effect on growth and yield of *B. campestris* and *T. aestivum* during entire study period *i.e.* 2012-16. The yield of *B. campestris* in open plot was recorded 108.63 and 68.72 g m^{-2} during 2012-13 & 2013-14, respectively, while in case of *T. aestivum*, it was recorded 413.23 and 321.67 g m^{-2} during 2014-15 & 2015-16, respectively. Planting of *A. senegal, C. limon* and *A. marmelos* reduced the yields. The per cent reduction in yield of *B. campestris* in association with different woody species ranged between 35-58% and 39-55% during 2012-13 & 2013-14, respectively. Similarly, in *T. aestivum*, it ranged between 15-24% and 46-61% during 2014-15 & 2015-16, respectively. Distance from tree base significantly affected growth and yield of understory crops. All growth and yield attributes of test crops decreased maximum in closer vicinity of tree trunk at 1.0 m and minimum at 4.5 m from the tree base. Plant population (m^{-2}) of both test crops was minimum at 1.0 m distances, and maximum at 4.5 m away from tree base, during entire study period. The minimum number of plants near the tree base was attributed to low sunlight received by the understory crops (Newaj *et al*., 2007; Shukla *et al*., 2009). Low population of understory crops beneath the tree canopy may primarily be due to less seed germination (Vandelook *et al*., 2008). Maximum growth and yield attributes of crops were recorded at 4.5 m distance from tree base. Decrease in yield loss at 1.0 and 2.5 m distances from tree base were compared with the yield recorded at 4.5 m distance. The per cent decrease in yield of *B. campestris* due to closer distances from tree trunk was 13-84% and 21-69% during 2012-13 & 2013-14, respectively, and in *T. aestivum*, it ranged between 22-34% and 29-41% during 2014-15 & 2015-16, respectively. Reduced crop yield near the tree base has been reported by various researchers under different conditions (Puri *et al*., 1995; Puri and Sharma, 2002). In gum-arabic (*A.*

senegal) based agroforestry model, *T. aestivum* was found to be more compatible than *B. campestris* as the later suffered more losses in terms of crop yield. The yield from fruit components and gum-arabic is likely to compensate the losses in crop yield which will make system more viable and sustainable.

Rainfed agroforestry model

This model was established in the year 2012 to study the effect of spacing on survival, growth and biomass production from *A. nilotica* and *A. senegal based agri-silviculture* system in rainfed condition. The dimension of the selected field was 65 m long and 180 m wide. Entire field was demarcated into three blocks (65×60 m each) wherein *A. nilotica* and *A. senegal* were planted in different spacing regimes *viz*., 10×10 (density: 100 trees ha^{-1}), 10×5 (density: 200 trees ha^{-1}) and 5×5 m (density: 400 trees ha^{-1}). There are six rows in 10×10 m block, six rows in 10×5 m block and 12 rows in 5×5 m block. In each block, each row of *A. nilotica* is being alternated with the row of *A. senegal*. There are seven plants in each row of 10×10 m spacing block; 14 plants in each row of 10×5 m spacing block; and 14 plants in each row of 5×5 m spacing block. A total of 42 plants (21 *A. nilotica* and 21 *A. senegal*; total six rows) in 10×10 m; 84 plants (42 *A. nilotica* and 42 *A. senegal*; total six rows) in 10×5 m; and 168 plants (84 *A. nilotica* and 84 *A. senegal*; total 12 rows) in 5×5 m spacing have been planted. Six-month old seedlings were planted. The cropping sequence adopted for this model is *Vigna radiata/Sesamum indicum-Eruca sativa* for rainy-winter seasons. Standard package of practices for these intercrops were adopted during the period of cultivation (Plate 9 A, B & C). The growth performance of trees after eight years of planting has been given in Table 6.

Prasad *et al.* (2020a) reported that both the species recorded maximum canopy spread and utilizable biomass (kg $tree^{-1}$) in 10×10 and minimum in 5×5 m spacing (Table 7); however, total biomass (tons ha^{-1}) was found higher in close spacing (5×5 m) (Figure 5). Apart from this, *A. senegal* (37.63 g $tree^{-1}$) and *A. nilotica* (12.21 g $tree^{-1}$) started yielding gums after five years of plantation. This plantation is expected to yield good quantum of gum in coming years that can be an added advantage to the local inhabitants.

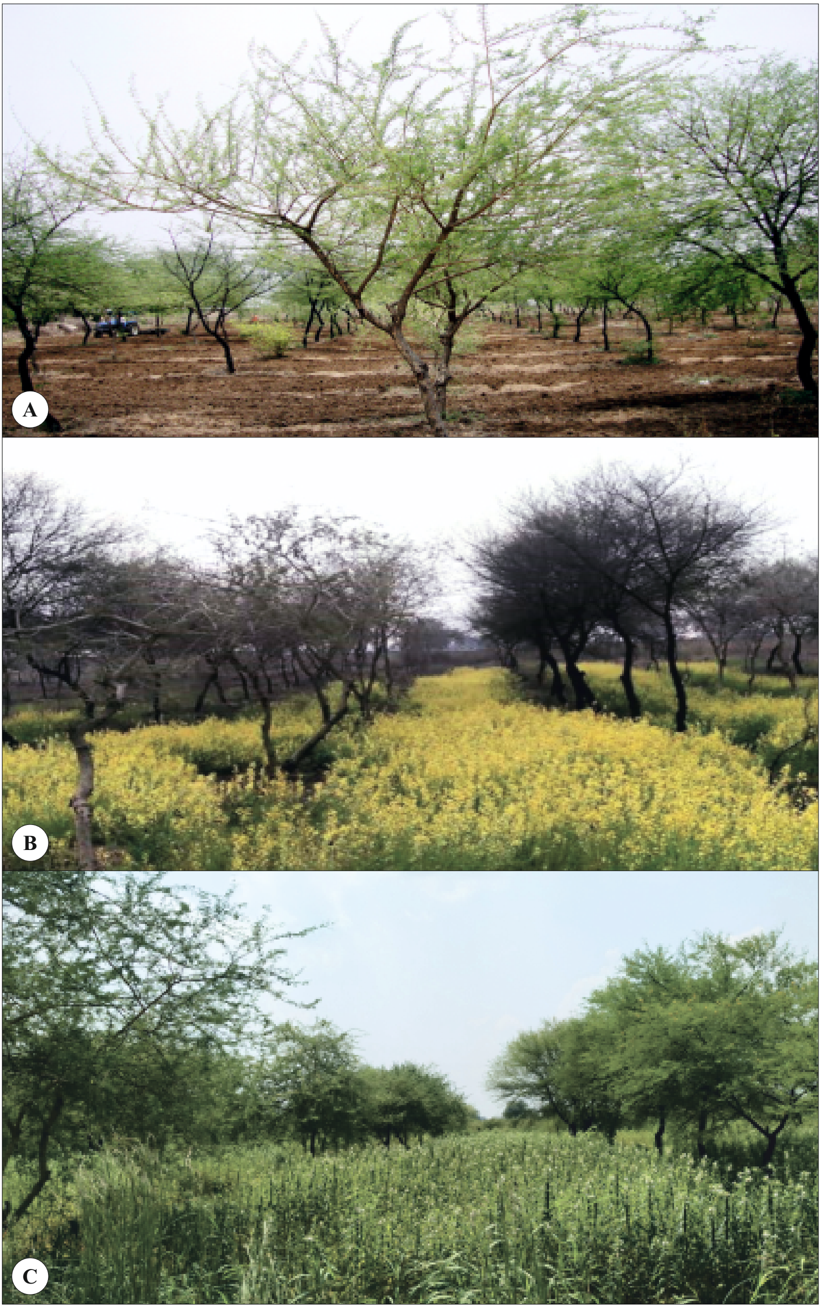


Plate 9. ***A. senegal*** **based rainfed agroforestry model (A), alongwith growing intercrops** ***E. sativa*** **(B) and** ***S.indicum*** **(C)**

Table 6. Growth of eight-year old gum-yielding trees in a rainfed agri-silviculure model

Growth parameters	*Acacia senegal*			Mean	*Acacia nilotia*			Mean
	10×10m	10×5m	5×5m		10×10m	10×5m	5×5m	
GBH (cm)	36.2	27.4	30.5	31.4	39.3	33.5	33.4	35.4
Height (cm)	509.2	454.4	519.3	494.3	554.7	484.3	511.2	516.7

Table 7. Utilizable biomass production from *A. senegal* and *A. nilotica* in a rainfed agri-silviculture model

Plant species/ spacing	2015 (3YAP)*	2016 (4YAP)	2017 (5YAP)	2018 (6YAP)
Acacia senegal				
10×10 m	8.73±0.35	2.91±0.46	3.66±0.34	4.31±0.61
10×5 m	6.68±0.87	2.90±0.72	3.60±0.31	3.25±0.46
5×5 m	5.72±0.72	2.56±1.00	3.21±0.38	3.19±0.29
F-ratio	72.346	0.690	10.750	22.082
P-value	<0.001	0.510	<0.001	<0.001
LSD0.05	0.63	NS	0.32	0.43
Acacia nilotica				
10×10 m	7.34±1.00	3.59±0.64	4.96±0.68	5.36±1.04
10×5 m	5.98±0.47	3.34±0.26	4.71±0.41	4.77±0.29
5×5 m	4.87±0.41	3.12±0.25	4.28±0.26	4.09±0.67
F-ratio	33.043	3.111	5.143	7.430
P-value	<0.001	0.061	0.013	0.003
LSD0.05	0.62	NS	0.44	0.67

*Year after planting (YAP)

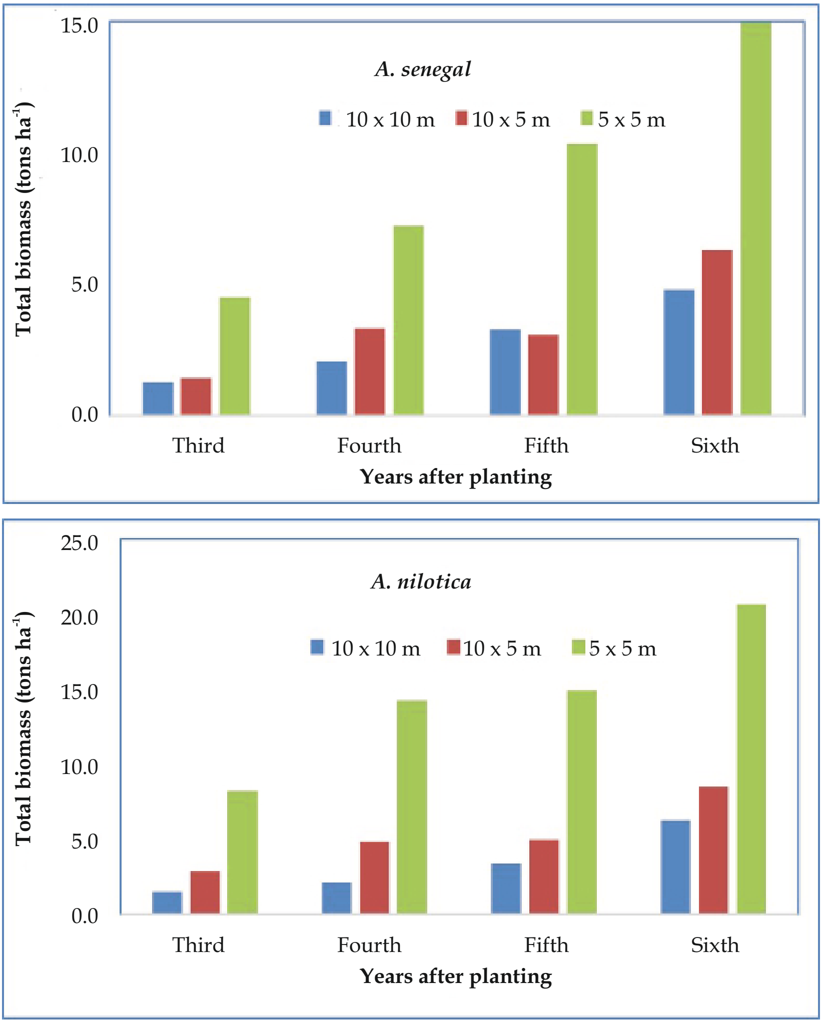


Figure 5. Effect of age and spacing on total biomass production of *A. senegal* and *A. nilotica* in a rainfed agri-silviculture model

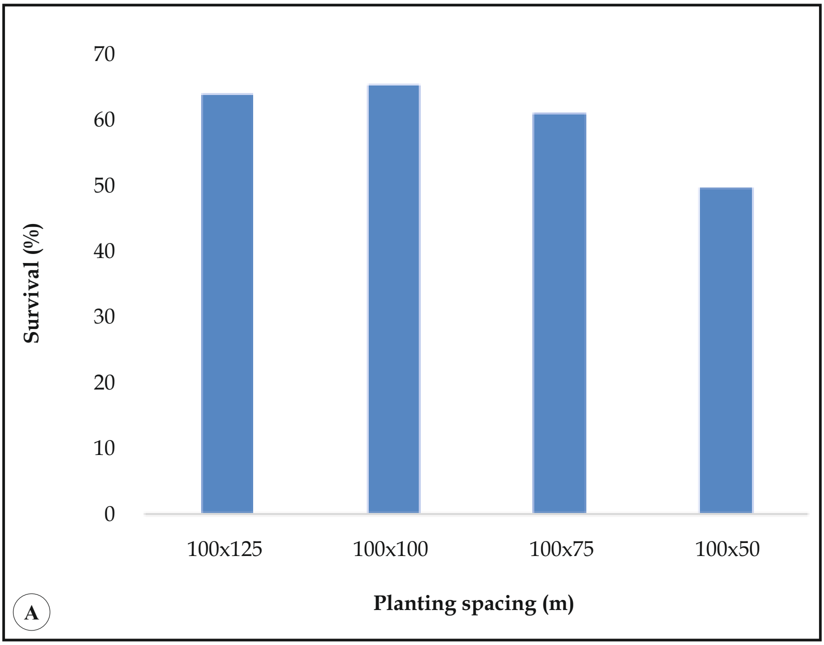
Prasad *et al.* (2022a) studied performance of inter-crops grown in this rainfed agri-silviculture model and reported that planting spacing of *A. senegal* and *A. nilotica* had a significant effect on the growth and yield of understory crops. Wide planting yielded the maximum growth and yield of intercrops, while close planting produced the minimum. The magnitude of percentage decrease in yield of understory crops in closer spacing (5×5 and 10×5 m) over wider spacing (10×10 m) varied from -29.7 to -13.7% in *V. radiata* (2019); from -25.0 to -8.7 in *E. sativa*

(2019-20); from -35.8 to -26.6 in *S. indicum (*in the year 2020); and from -25.0 to -12.0% in *E. sativa* (2020-21), irrespective of planted species. Growth and yield of understory crops were relatively better in association with *A. nilotica* than with *A. senegal*. The study suggested that planting both species at 10 × 5 m spacing in the Bundelkhand region is feasible with little impact on understory crop yield. This spacing may also yield higher green fodder (utilizable biomass) when compared with close-spaced plantations, as moderate spacing recorded comparatively higher canopy spread than close spacing.

Silvi-herbal model

Silvi-herbal model has been developed with integration of lemongrass in alleys of *Acacia senegal* and *A. nilotica* planted apart 18m. Within the row *A. senegal* and *A. nilotica* has been planted 6m apart. The planting of *A. senegal* and *A. nilotica* was done in 2009 and lemongrass has been integrated and planted in 2020 (Plate 10). Root slips of lemongrass were planted using four different spacing with four replications. In different replications, a total of 164 root-slips were planted in spacing of 100 × 50 cm; 112 in 100 × 75 cm, 84 in 100 × 100 cm and 68 in 100 × 125 cm. After two years of planting, the survival (%) of lemongrass was mximum in 100 × 100 cm (64.7%), followed by 100 × 125 cm (63.2%), 100 × 75 cm (60.4%) and 100 × 50 cm (49.2%). After 10 years *Acacia nilotica* attained height of 9.7m with 97.2cm GBH, while respective values for *Acacia senegal* were 4.4m and 31.0cm. The survival, growth of lemongrass tussock and biomass production was affected by the planting spacing of lemongrass. The maximum survival and growth of lemon grass tussock and biomass production was observed in tussocks planted at 100×100cm spacing (Figure 6 A & B).

Plate 10. ***Acacia*** **+ lemon grass based silvi-herbal model**



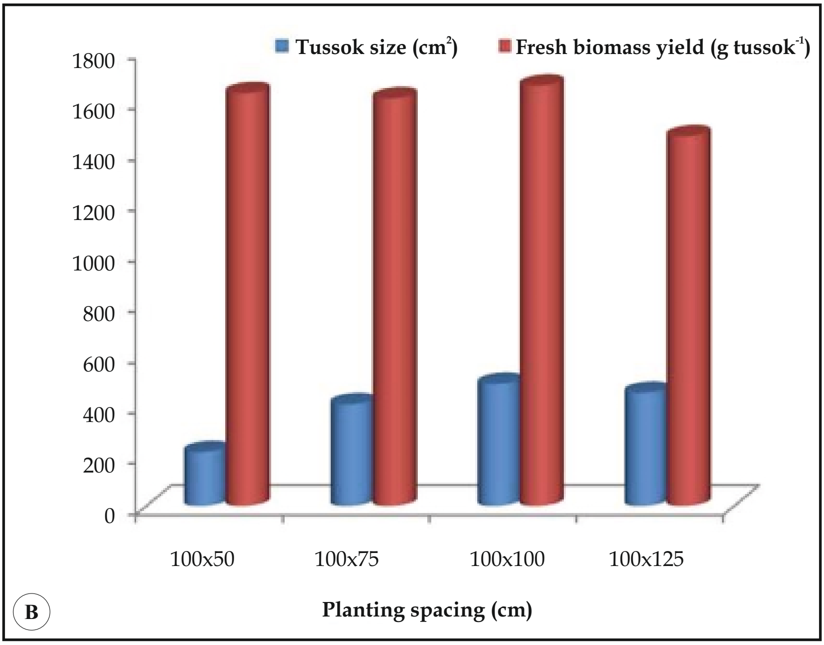


Figure 6. Survival (A), growth and biomass production (B) of lemon grass in *A. senegal* based silvi-herbal model

Bio-fence model

Four different bio-fence models based on *Acacia senegal* have been developed at research farm of ICAR-CAFRI, Jhansi in the year 2018 aiming to study effectiveness and also demonstrate to farmers. Bio-fence model-1 is aimed to optimize the distance apart *A. senegal* and *C. carandas* (1.0, 1.5 and 2.0 m apart) in single row; bio-fence model-2 is aimed to assess the effectiveness of double row fence consisting of *A. senegal* as outer row and *C. carandas* as inner row (Plate 11 A); bio-fence model-3 is aimed to assess the effectiveness of double row fence of *A. senegal* at different spacing on three sides of field boundary of a well-established *Emblica officinalis* orchard (Plate 11 B) and bio-fence model-4 is aimed to assess the effectiveness of two rows of *A. senegal* (inner and outer) kept at 1.5 m apart with plant to plant distance of 1.5 m, planted along two sides of a well-established *Punica granatum* orchard.

Table 8. Plant growth in different bio-fence models after 3 years of planting

Bio-fence models	CD (mm)	Height (cm)	Canopy spread (m^2)
Model-1 (Single row)			
Acacia senegal	36.3	1.8	1.5
Carissa carandas	5.0	0.4	0.1
Model-2 (Double row)			
Acacia senegal	28.1	1.7	1.9
Carissa carandas	5.8	0.4	0.1
Model-3 (Double row)			
Side 1			
Acacia senegal (outer row) - 1.0 m	24.4	1.8	0.5
Acacia senegal (outer row) - 1.5 m	44.4	2.5	1.3
Side 2			
Acacia senegal (outer row) - 2.0 m	24.9	2.0	0.8
Acacia senegal (inner row) - 1.0 m	43.7	2.4	1.1
Side 3			
Acacia senegal (inner row) - 1.5 m	35.7	2.1	1.0
Acacia senegal (inner row) - 2.0 m	42.7	2.4	1.5
Model-4 (Double row)			
Acacia senegal (outer row)	21.68	122.4	0.29
Acacia senegal (inner row)	27.02	144.59	0.72

In bio-fence model-1, *A. senegal* have attained 36.3 mm collar diameter with 1.8m height, and *C. carandas* recorded 5 mm collar diameter with 0.41m height. In bio-fence model-2, *A. senegal* have attained 28.1 mm collar diameter with 1.7m height, and *C. carandas* recorded 5.8 mm collar diameter with 0.4 m height (Table 8). In bio-fence model-3, planting spacing has affected growth of the *A. senegal*. In general, comparatively higher growth in terms of collar diameter and height was recorded from *A. senegal* planted in inner row than that from outer row. In bio-fence model-4 consisting of two rows of *A. senegal* (inner and outer) kept at 1.5 m apart with plant to plant distance of 1.5 m, the growth of *A. senegal* planted in inner row was relatively higher than that planted in outer row.

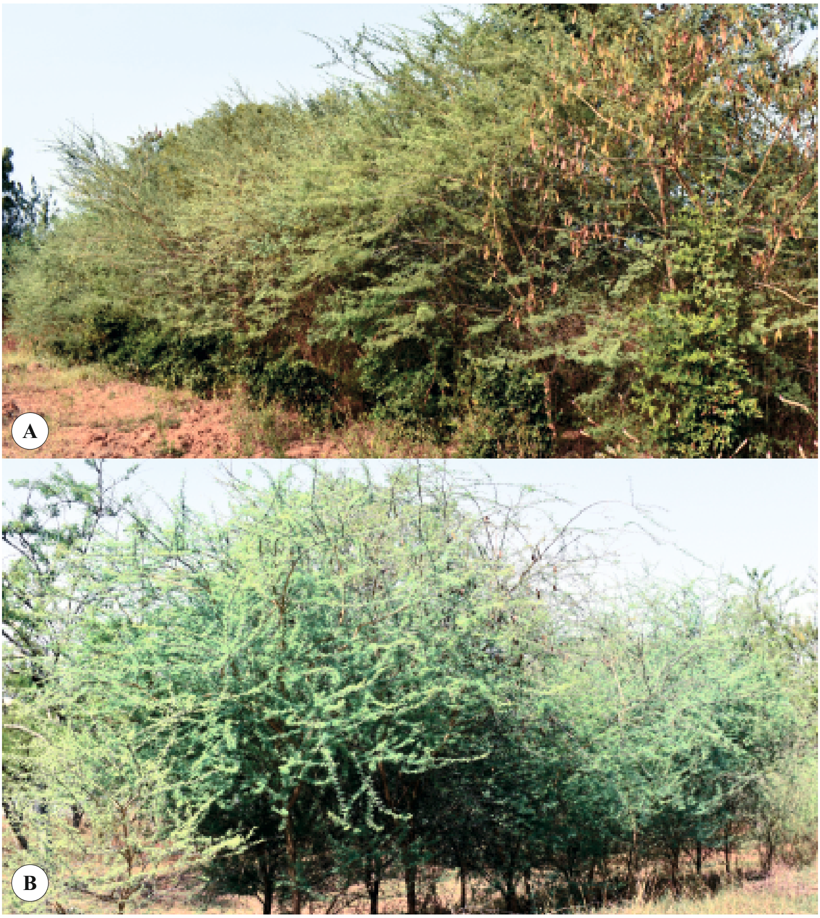


Plate 11. ***A. senegal*** **based staggered double row bio-fence model:** ***A. senegal*** **+** ***C. carandas*** **(A) and double row** ***A. senegal*** **(B)**

For effectiveness against the stray cattle, the most pertinent part of the bio-fence is its penetrability. It was measured by projecting the vertical face of the bio-fence to assess the percentage occupancy using Digitiser V 6.3.0 tool. One side of 5 years old *Acacia senegal* + *Carissa carandas* based double-row bio-fence was assessed. The length of fence was 47.0m. *Acacia senegal* and *Carissa carandas* were planted at spacing of 2m each and spacing between the row was 2m. The height of the *Acacia senegal* was 3.6±1.1m; canopy width was 3.4±0.96m and canopy height was 2.9±1.2m. The height of *Carissa carandas* was 0.8±0.4m. Based on the data analysis, it is revealed that the projected ground area occupancy (47m X 2m) was 94 m^2 out of the the actual ground area occupancy of 160.0 ± 44.0 m^2. This is mainly because of the expanding canopy width of the *Acacia senegal.* The rectangular vertical area occupied by the bio-fence was 60.97 m^2. The opening was demarcated and measured for the area and the data indicates that ~13% vertical projection of the bio-fence had opening/gap and the actual vertical area occupied by the fence was 53.15 m^2 (Plate 12). The opening/gap at the bottom part of the fence requires routine management.

Plate 12. Close-up view of 5-year old *A. senegal* bio-fence analysed for opening/gaps

Block plantation model as gum garden

A. senegal based gum garden has been established in degraded rocky land of ICAR-CAFRI research farm by planting at 3×3 m and 3x2m spacing in three phases during 2009- 2015 (Plate 13). The growth of *A. senegal* in gum gardens is given in Table 9. In plantation at rocky hillock, about 200 seedlings of *A. senegal* were planted during 2009. After 10 years, the total numbers of plants have increased to about 350 due to natural regeneration. Growth of *A. senegal* was better in rocky food hills-II in comparison to other two locations.

Plate 13. *A. senegal* based gum garden planted at degraded rocky site in Bundelkhand

Table 9. Growth of *A. senegal* in gum garden at degraded rocky site in Bundelkhand

Type of land/ plantation	Spacing	Age (year)	Survival (%)	GBH (cm)	Height (cm)
Rocky hill (block plantation)	3 m × 2 m	12	100	22.3	466.5
Degraded rocky area foot hills-I (gum garden 1)	3 m × 3 m	8	73.7	15.5	321.9
Degraded rocky area foot hills-II (gum garden 2)	3 m × 3 m	7	90.7	31.3	251.2

Economic Viability and Climatic Resilience of *Acacia senegal* based Agroforestry Model

The multifaceted benefits from of agroforestry include supply of fuel, wood, fodder and food; non timber forest products (natural resins and gums (NRGs)); carbon sequestration, improvement in soil quality and increase in resilience against uncertainties of climate change in agriculture (Davis *et al.*, 2012). Further, the agroforestry landuse holds great potential for providing economical, ecological and cultural benefits to the society at large. Despite huge potential and accrued benefits from the agroforestry, its diffusion among various stakeholders is lagging behind in the world (Mercer, 2004); and in India too, adoption of agroforestry by smallholders has remained almost similar to the global trend (Prasad *et al.*, 2018c). Out of many constraints, the most important reason for non adoption of agroforestry in India appears to be its long juvenile phase during which resource poor small and marginal farmers do not get any returns and consequently refrain from adopting agroforestry on their farmlands.

High economic efficiency of limited resources manifested by better returns per rupee invested remains main attraction and driving force behind adoption of agroforestry by smallholders. Today, many agroforestry models are increasingly being recognized as a viable farming system and widely promoted for achieving twin objective of food security and climatic resilience without their proper economic analysis and documentation. Various scholars have studied financial and economic profit of different agroforestry systems practiced in India (Sharma and McGregor, 1991; Jain and Singh, 2000; Dwivedi *et al.*, 2007; Chavan and Dhillon, 2019). It is often argued that the traditional rules of economics and financial analyses do not hold true in analyzing agroforestry systems because of their complexity and site specificity. The profitability from agroforestry remains highly dependent on location and site specific characteristics, and that's why the role of many alternative agroforestry systems embracing specific produce such as natural gum and resins acquire significance. In India, around 30 plant species have been identified as resin and gum-yielding species. The Important gum and resins yielding trees are *Sterculia urens* Roxb. (gum-karaya), *Acacia nilotica* (L.) (gum-acacia), *Acacia senegal* L.

(Willd.) (gum-arabic), *Butea monosperma* (Lam.) Taub. (kamarkas), *Anogeissus latifolia* Roxb. (gum dhawara) and *Tamarindus indica* L. (tamarind-gum). *Acacia senegal* is integrated in agroforestry land-use in arid and semi-arid regions of the world (Raddad and Luukkanen, 2007; Prasad *et al*., 2018c; Omokhafe, 2019; Prasad *et al*., 2015). Several intercrops have been tested in *A. senegal* based agroforestry system throughout the world (Fadl and Gebauer, 2004, 2005; Fadl and Sheikh, 2010; Fadl, 2013; Prasad *et al*., 2018a). Farmers generally prefer fruit-producing species for planting on their farms due to their potential for income generation. Fruit trees are considered advantageous because they offer uniform distribution of income throughout the year. Since, agroforestry remains productive for the farmers by generating continuous income, the farmers are always inclined to adopt such land-use system for maximizing their profits. The economic analysis of agroforestry is more complicated than that of annual crops for two main reasons. Firstly, agroforestry is quite complex because it involves both trees and crops; and secondly, usually there is a period of several years between time of tree's establishment and appearance of its beneficial impact (Franzel, 2004).

Prasad *et al.* (2020a) studied benefit-cost analysis of ten years-old *Acacia senegal* based multi-component agri-horti-silviculture model suitable for small farmers. The main objectives of this study were to provide benefit-cost analysis of *A. senegal* based agri-horti-silviculture model so that smallholders can be motivated for adopting agroforestry on their farms, and to assess how integration of three horticultural fruit plant species in the model increases risk bearing capacity against vulnerability to climate change and make the model more climate resilient. The model established in the year 2009 covering 0.5 ha area comprised of one gum-yielding (*A. senegal*) and three fruit-yielding plant species (*A. marmelos*, *C. limon* and *C. carandas*). Intercropping commenced from 2009 and continued thereafter for 10 years. The cropping sequence of *P. mungo*/*V. radiata*–*L. culinaris*/*B. campestris*/*T. aestivum* was adopted for summer-winter seasons. For crop cultivation, standard package of practices was followed. Out of ten seasons, summer crops either failed or performed poorly during five seasons (2012-13 to 2016-17) which affected total returns from the agri-horti-silviculture model. For economic analysis of the model, benefit: cost (B:C) ratio, net present value (NPV), internal rate of return (IRR) and payback period (PBP) were used as measures of economic efficiency. The B:C ratio is an economic indicator for the rate of returns per rupee invested and it was calculated on annual basis as well as at discounted rate of 12% for whole period of 10 years. The NPV was calculated to show present worth of the model. The NPV criterion is the principal project evaluation criterion. The NPV is merely the algebraic difference between discounted benefits and discounted costs as they occur over time. IRR is the annual earning rate of the project. It is calculated to present the capacity of model to generate regular profit and for comparison with cost of capital. The PBP represents length of time required for the stream of cash proceeds produced by the investment to be equal to the original cash outlay i.e. the time required for model to pay for itself. The PBP of the agroforestry model was calculated to show the time period in which the model will be able to generate sufficient revenue to cover all the 10 years cost involved in different years and when this model turns profitable. Economic analysis of the agri-horti-silvicultural model was done on the basis of the opportunity costs of different inputs (Kumar and Singh, 2017).

Data on summary of undiscounted benefit-cost analysis indicated that during 1st year, the annual B:C ratio was 0.74 implying that there was net loss against investment in the agri-horti-silviculture model. In 2nd year also the annual B:C ratio remained less than 1.0, and during 3rd to 5th year, it remained almost static around 1.0; thereafter, it increased considerably and reached up to 2.15 in 10th year (Table 10 and Figure 7).

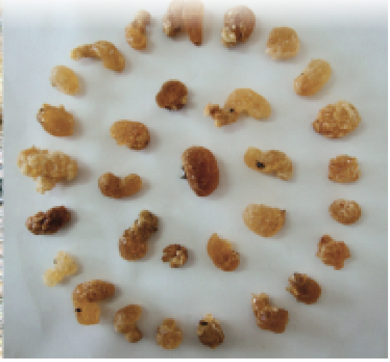


Table 10. Summary of benefit-cost analysis of *A. senegal* based multi-component agri-horti-silviculture model for ten years

Year	Intercrop grown		Total cost of cultivation (Rs.)	Total returns (Rs.)	Annual B:C ratio	B:C ratio (two periods of 5 years each)
	Summer	Winter				
2009-10	*P. mungo*	*B. campestris*	42280*	31348	0.74	0.93
2010-11	*P. mungo*	*L. culinaris*	25863@	21682	0.84	
2011-12	*P. mungo*	*B. campestris*	31338	33756	1.08	
2012-13	Poor/ Failed	*B. campestris*	22165$	21908	0.99	
2013-14	Poor/ Failed	*B. campestris*	21463$	21532	1.00	
2014-15	Poor/ Failed	*T. aestivum*	43278#	51530	1.19	1.52
2015-16	Poor/ Failed	*T. aestivum*	41907$	53188	1.26	
2016-17	Poor/ Failed	*T. aestivum*	49256$	78670	1.60	
2017-18	*V. radiata*	*B. campestris*	43510	61818	1.42	
2018-19	*P. mungo*	*T. aestivum*	59125	127284	2.15	
Annualized average for ten years			38019	50272	1.32	1.32

*Includes cost of establishment of agroforestry model during first year; @Includes cost of maintenance of agroforestry model during subsequent years; $Summer crop was not sown; #Summer crop was sown but failed and benefits accrued as green manuring not accounted

For first five-year period, the B:C ratio was 0.93 whereas it was 1.52 for the span of second five-year. For a total 10-year period, the annualized average B:C ratio was worked out to be 1.32.

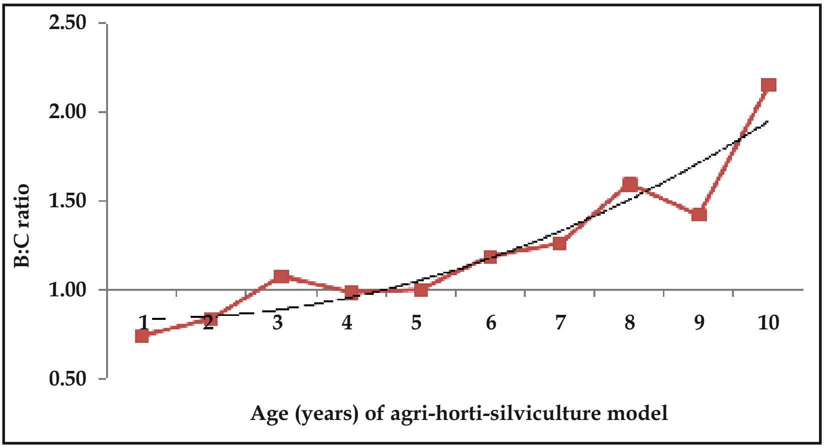


Figure 7. Variations in annual B:C ratio of *A. senegal* based multi-component agri-horti-silviculture model over a period of ten years

At discount rate of 12%, summary of discounted cost, returns and B:C ratio, NPV, IRR and PBP has been given in Table 11. The total discounted cost for model of 10 years was found as Rs. 202442 ha^{-1} and discounted total returns was found as Rs. 240656 ha^{-1}.

The discounted B:C ratio was found as 1.19 for model. The NPV of model (discounted total returns-discounted total cost) reflecting the current worth of model, was found as Rs. 38214 ha^{-1}. The IRR was found as 18.29%, which was sufficiently above the rate of interest of 12%. Thus, the model was suitable for adoption by the smallholder farmers. On the basis of annual returns from the model, the PBP was 8.41 years. It implies that in this period, the total cost of the model spent in 10 years was recovered and thereafter model has started generating net profits only.

The component-wise returns from agri-horti-silviculture model were not always static, and it faced ups and down due to poor and/or failed summer crop, while returns from tree components increased continuously from 3rd year onwards (Figure 8). During the period of ten years, maximum loss due to failure of summer crops was equated with the maximum returns from the successful summer crop which was Rs. 17960 ha^{-1} obtained in the 9th year (2017-18).

Table 11. Discounted cost, returns and B:C ratio at 12% discount rate for *A. senegal* based multi-component agri-horti-silviculture model for ten years

Year	Discounted total cost (Rs. ha^{-1})	Discounted total returns (Rs. ha^{-1}))	NPV (Rs. ha^{-1})
2009-10	37750	27989	-9761
2010-11	20618	17285	-3333
2011-12	22306	24027	1721
2012-13	14086	13923	-163
2013-14	12179	12218	39
2014-15	21926	26107	4181
2015-16	18957	24060	5103
2016-17	19894	31773	11880
2017-18	15690	22292	6602
2018-19	19037	40982	21945
Total	202442	240656	38214
Average	20244	24066	
B:C ratio at discounted rate of 12% after ten years			1.19
IRR after ten years (%)			18.29
PBP (years)		8.41	

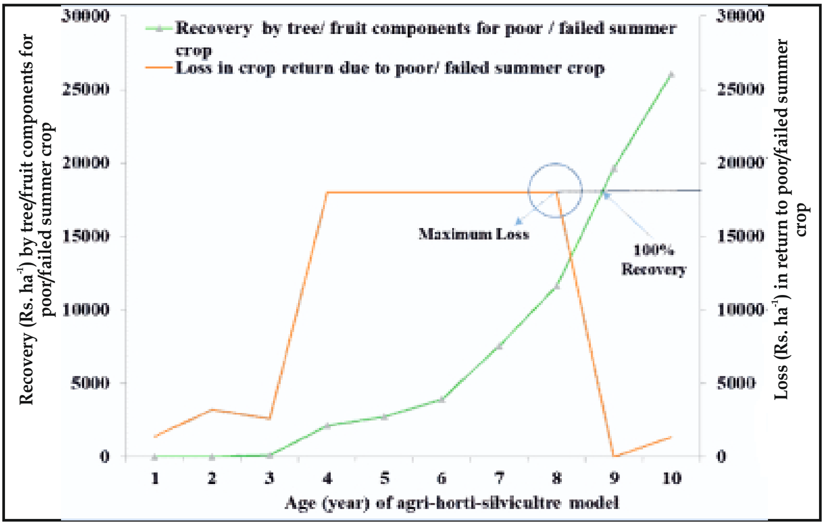


Figure 8. Recovery by tree/fruit component for losses due to poor/failed summer crop in *A. senegal* based multi-component agri-horti-silviculture model

Winter season crop never failed, however, returns from winter crop varied and depended on the type of crops cultivated and its performance. Despite failure of summer crop during the 4th to 8th year, the annual B:C ratio either maintained around 1.0 or was more than 1.0 implying that the failed crop losses were compensated by usufructs from woody components which started giving return from 3rd year onwards and from horticulture component which started giving return from the 4th year onward (Figure 8). These results suggested that tree/fruit components reduced payback period of the model exhibiting its potential to act as a sink for climate related risks in agricultural production system. More or less similar result has also been reported by Singh *et al*. (1997) in northwestern India. They reported comparatively reduced annual B:C ratio in case of agroforestry than pure crop (rice and wheat) during first three years. Multiple components in agroforestry system can cover up the risk factor, as in present study fruit plants efficiently covered the risks of climatic vulnerability. Establishment of fruit trees in agricultural fields is a long-term and sustainable way of investment, because once the trees bear fruits, they provide the farmers with a regular flow of cash income for many years (Snelder *et al*., 2007). Production of gum-arabic from *A. senegal* can also help in covering up the risk and may provide revenue. In present study, *A. senegal* started yielding gum naturally 6th years onward. Increase in its production was noticed with the age of the model. The gum-arabic is highly valuable and fetches Rs. 600-800 kg^{-1} in the market. In India, average yield of gum-arabic per tree varies from 175 to 550 g tree^{-1}year^{-1} (Prasad *et al*., 2015), while in Sudan, from 0.9 kg (younger trees) to 2.0 kg (older trees). Thus, more returns from *A. senegal* in form of gum-arabic is expected from agri-horti-silviculture model in future. Further, results of the study showed that such a smallholding model could compensate 100% loss of failed summer crop after 8.41 years (Figure 8). The summer crops (*P. mungo* or *V. radiata*) always remained at risk due to abnormal monsoon rain which can create insecurity in terms of food supply. Multiple component based agroforestry system can successfully combat food insecurity by responding to challenges and opportunities related to climate change (Lasco *et al*., 2009; Tsuji *et al*., 2019). The general decline in per cent share of returns from intercropping in total returns from agri-horti-silviculture model was noticed. After ten years, it was recorded up to 20% which was compensated fully by increasing share of tree/woody components of the model (Figure 9).

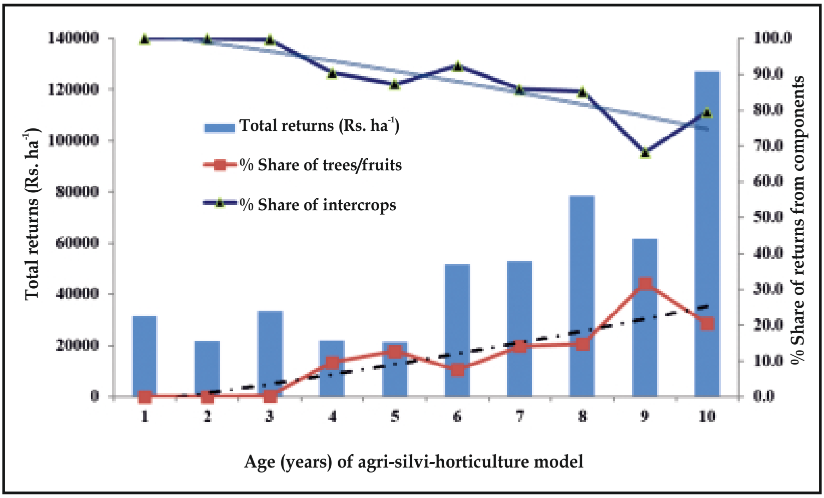


Figure 9. Share of different components of *A. senegal* based multi-component agri-horti-silviculture model in total returns

After ten years of establishment of the model, the annual B:C ratio of 2.15 indicates that a farmer may earn Rs. 2.15 against per rupee invested in agri-horti-silviculture model on his farm, and this rate of returns is likely to increase further with increase in the returns from tree/woody components with the age of the model. It is hoped that this type of financial analysis based on scientific data will motivate small farmers to adopt *Acacia senegal* based agroforestry.

Chapter 8 Utilization

Economic Products

Gum (gum arabic)

The most recognizable product of *Acacia senegal* is gum arabic- a significant global commodity because of its many industrial and culinary uses (Bennett, 2000). Gum arabic is the carbohydrate secretions produced by stems or branches of *Acacia* trees when injured naturally, by animal or by humans, in interaction with bacteria, fungus or any other physical interactions. Gum is also obtained by cutting the bark of the tree at the start of the dry season that enables gummosis, a process which triggers naturally after the bark has been damaged (Lesueur *et al.*, 2008). Rana *et al.* (2011) reported that plant gum exudates are the result of protection mechanism against mechanical or microbial injury. A positive correlation between the beetle *Agrilus nubeculosus* and gum arabic production by *Acacia senegal* have also been observed by Khalil *et al.* (2013), where some trees were tapped and left open to facilitate infestation by *A. nubeculosus* and the others were covered with wire mesh as control. In this *A. senegal* infested by *A. nubeculosus* produced significantly more gum than the control trees. Infestation also caused significant changes in some physical and chemical properties of gum (ferrous, calcium, magnesium and nitrogen contents), whereas, no significant difference was recorded in phosphorus and manganese contents. *Aspergillus flavus* Link. and *Pseudomonas pseudoalcaligenes* Monias isolated from the mouth parts of *A. nubeculosus*, when inoculated to the tapped branches of *A. senegal* with a suspension of *A. flavus* alone or in combination with *P. pseudoalcaligenes*, resulted in significantly high gum yield as compared to the control. It seems that *A. flavus* and *P. pseudoalcaligenes* acted as elicitors that have stimulated the synthesis of gum arabic. *A. nubeculosus* transmitted *A. flavus* and *P. pseudoalcaligenes* to the tapped areas.

The period of gum tapping is the hot dry season as gum formation requires intense heat and dehydration stress. The exudate takes about 3 weeks to collect after the initial slit is made and can be collected several times throughout the season from the same tree (Anderson, 1995). Tapping begins when trees are 4-5 years old and generally commences after leaf fall and ceases during the colder months. Gum nodules form in 3-8 weeks, exuding from the former broken abscission scars. Annual gum yields stand at 188-2856 g for young trees and 379-6754 g for older trees (7-15 years), but gum production is highly dependent on origin, plody level, population density, soil type and site conditions (Wekesa *et al*., 2009; Chikamai and Odera, 2002; Diallo *et al*., 2015). For example, *A. senegal* in arid zone of Rajasthan produces 0.41 kg tree^{-1} gum arabic on sand dunes, 0.32 kg tree^{-1} in inter dune area and minimum of 0.12 kg tree^{-1} on rocky gravelly land forms (Pareek *et al*., 2017). Density of *A. senegal* gum found to be strongly related to temperature (Rabal, 2011)). Gum viscosity varies linearly with concentration, but at high concentration (>10 g/L) it varies exponentially. In western India, gum production is generally poor under natural conditions (15-25 g tree^{-1}). It is induced by injecting ethephone (commercial preparation of 2-chloroethyl phosphonic acid) during March to May in 2-2.5 cm deep hole made in stem of about 8-year-old trees (above 20-25 cm height from the ground) to get gum up to 300 g tree^{-1} in rocky areas to 500 g tree^{-1} in sandy areas (Harsh *et al*., 2003; Ram *et al*., 2011; Tewari, 2012).

The variation in annual gum productions is because of variations in optimum tapping, rainfall, tree age and soils texture (Abdelrahman *et al*., 2003; Harmand *et al*., 2012). For example, average gum production varies from 100 to 500 g per tapped tree, corresponding to 50-250 kg ha^{-1} with a density of 500 trees ha^{-1} in a rainfall zone of 650 to 800 mm annually. However, Unanaonwi (2011) observed nitrogen as main factor accounting for 99% of the variation in gum yield, whereas increased gum yield was related to decreased calcium levels (Muthana, 1988). The gum production was positively correlated to soil water at 75-150 cm soil depth (Gaafar, 2005). Oleghe and Akinnifesi (1992) observed that adequate water supply helps the production of gum in the dry season in the Nigerian Sahel. In Senegal, Giffart (1973), Sene (1988) and Dione (1996) observed that significant rainfall during the rainy season, followed by a hot dry season support gum production. Prasad *et al*. (2022b) assessed the relationship between natural gum exudation in *A. senegal* and soil moisture content (%) of agroforestry system (0-30 cm depth) in both rainfed and irrigated conditions in Bundelkhand, a typical semi-arid region of Central India. They reported that positive but non-significant correlation existed between soil moisture (r=0.236) and mean gum yield and number of trees exuding gum under irrigated condition. Total annual rainfall in preceding year showed direct influence on the number of trees with multiple exudations in a year (r=0.763). Contrary to the irrigated conditions, in rainfed agroforestry, total gum yield exhibited better degree of positive correlation with soil moisture content (r=0.559). The study further revealed that the number of trees exuding gum also increased with soil moisture as evidenced by significant positive correlation (r=0.676) between the two. Significant positive correlation also existed between total gum yield and number of trees with multiple exudations in a year (r=0.957). Rainfall in preceding month of the same year had direct effect on mean gum yield. The soil moisture content has triggered multiple exudations as revealed by significant positive correlation between soil moisture and number of trees with multiple exudations in a year. It is concluded that better monsoon years are likely to yield more gums from *A. senegal.* The chemical composition of gum arabic differs according to its botanic origin and not according to its geographic distribution. Its specific weight is 1.487. One of its very important characteristics is that it is insoluble in ether, chloroform and pure alcohol, but highly soluble in water. It forms a liquid of weak acidity easy to be broken by boiling. It dissolves in diluted sulfuric acid to three mono sugars (44% of hexagonal galactose, 02% penta arabinose, 14% aramtose with 15% of gloconic acid, 02% proteins).

Gum as food contains few calories. It is a good stabiliser of flavour and smell, and a good binder. Being an emulsifier it is an excellent agent for homogeneity of solutions of different density with fats and oils. These properties make gum arabic very useful in several industries including food industry where it is used as a flavor and stabilizer of citrus oil emulsion concentrates in soft drinks (Dauqan and Abdullah, 2013). It is used as stiffener, a thickener, a creamer, a foamier, a bodier, a suspensor, a carrier, a sensitizer and a base. It is an appropriate medium which does not allow germs and microbes to grow. Gum arabic conserves iron-free foods, prevents change of colour of meat and milk and crystallization of sugar in drinks when cooled, and help reduce cholesterol in blood. It is also a controlling factor in the agglomeration of the proteinaceous components within the molecularly disperse system, where *A. senegal* gum increases the amount of arabinogalactan protein (Al-Assaf *et al.*, 2007). Because of these characteristics, gum arabic plays a big role in processing of desserts, jams, crackers beverages, food, medicines, cosmetics, inks and textile printing as well as nuclear reactors.

Properties of gum arabic obtained from *Acacia senegal* have been characterized by many researchers with specific purpose and standards. The general physical, chemical and micro-biological properties compiled by Mertia *et al.* (2009) and Uikey (2013) are reproduced here in Table 12.

Table 12. Physical, chemical and micro-biological properties of gum arabic (*A. senegal*)

Property	Values	Remark
Moisture content (%)	3.5	15% is the maximum limit for food and pharmaceutical use as per international specifications of IP, JECFA, USP and BP*
Ash content (%)	3.0-3.9	Total ash content should not exceed 4% as per international specifications of IP, JECFA, USP and BP*
pH	4.3-4.4	Acidic pH censes more irritation in gastroin-testinal tract
Nitrogen content (%)	0.27-0.44	High values are good. It indicates emulsifying behavior
Water insoluble matter (mg 5 g^{-1})	12.0	Should not exceed 50 mg
Loss on drying (%)	3.03	Should not exceed 15 per cent
Acid insoluble ash (%)	0.19	Should not exceed 1.0 per cent
Viscosity (CPS) at 40^0C	18	
Viscosity (CPS) at 100^0C	12	
Heavy metal (ppm)	<20	
APC g^{-1}	<1000	
Yeast and molds g^{-1}	<100	
E. coli (12.4 g^{-1})	Negative	
Salmonella (25 g^{-1})	Negative	
Staphylococcus aureus (10 g^{-1})	Negative	

IP = International pharmacopoeia; JECFA = Joint Expert Committee for Food Additive; USP = United State Pharmacopoeia; BP = British Pharmacopoeia

Seeds as vegetable

Dried seeds of *Acacia senegal* are used as food by humans. The seeds are dried and preserved for human consumption as a vegetable. However, there are chances of fungal contamination during long term storage and need special care (Bohra and Prohit, 1997). The dried seed is the main component of panchkut, a delicacy in western Rajasthan (Plate 14), India, that includes fruits of *Capparis decidua*, *Cucumis sativa* and *Prosopis cineraria* (Rathore and Meena, 2004).

Plate 14. Seeds of *A. senegal* used as constituent of Panchkut, a vegetable dish

Fodder

A. senegal leaves are of good nutritional value. Leaf protein content ranges from 15 to 33% of DM (dry matter) when fresh and low in fiber (crude fibre 14-25% of DM). The pods are also rich in protein but with a higher fiber content. Leaves and pods are browsed by sheep, goats and camels (Plate 15). *A. senegal* tree of 15.9 cm diameter can produce about 3.84 kg dry leaves and 1.34 kg dry fruits (Dicko and Sikena, 1991). Study in Rajasthan indicates that overall leaf production as fodder varied from 0.5 kg per tree to 3.6 kg per tree of girth ranging from 17.0 to 34.0 cm. Pod production ranges between 0.2 kg to 4 kg tree^{-1} having dbh range between 7.0 and 45.6 cm under agroforestry on farmers' lands (Singh *et al.*, 2020). Prasad *et al.* (2022b) reported that pruned foliage from 10 years old trees ranged from 3.24 (10×10m plantation) to 2.46 kg tree^{-1} (5×5m plantation). On per hectare basis, the utilizable green foliage was found maximum in 5×5m (984 kg ha^{-1}) and minimum (324 kg ha^{-1}) in 10×10m plantation. They opined that *A. senegal* can produce sufficient amount of utilizable foliage when planted in close spacing (5×5m) under rainfed conditions which may resolve the problem of fodder scarcity up to some extent in drought-prone Bundelkhand region of Central India.

Plate 15. New leaves of *A. senegal* browsed in lean/dry season by goats in Bundelkhand

Apiculture

A large proportion of the honey produced in tropical areas comes from trees, in contrast to the temperate regions where it is produced mostly from forage crops. *Prosopis* and *Acacia* species produce food for humans and fodder for animals within three to five years from seed, but also support a traditional income from beekeeping in the form of honey and beeswax (Townsend, 1998).

Fuel-wood

The wood of *Acacia senegal* is heavy and very strong. It provides an excellent fuelwood with calorific value at 3000 kcal kg^{-1}. However, Khider and Osman (2012) reported heat value for *A. senegal* up to 4620 Kcal kg^{-1}. Wood yields of 120-190 m^3 ha^{-1}, with annual increments of 0.5-1.0 m^3 ha^{-1} have been recorded. The dense wood also yields charcoal. When the trees are felled to allow cultivation, the wood is used for fuel, building materials and for fences around farm plots (Seif el Din and Zarroug, 1996). In African countries, *A. senegal* tree is subjected to felling before reaching twelve years of age for obtaining a quick return from fuel wood sales (El-Sammani, 1985; Mohamed, 2000).

Fibre

The long, flexible surface roots yield a strong fibre used for cordage, ropes and fishing nets (Rubanza *et al.,* 2007). A type of soluble fiber obtained from the sap of the *Acacia senegal* tree is also known as Acacia fibre.

Timber

The heartwood is almost black and takes polish well. It is used for making carts and Persian wheels, sugar cane crushers, agricultural implements, horse girths and tool handles. The average values for basic density of *Acacia senegal* wood is 728 kg m^{-3} that classify it as high – density wood (Bin, 1970). Wood production of natural stands is estimated at 4–7 m^3 per ha per year, whereas in plantations for gum yield the wood production is only 0.5–1 m^3 per ha per year. Tree biomass of *A. senegal* increases linearly with time from age 3 to 18 year and was linearly related to stem cross-sectional area at 30 cm height. Between ages 3 and 18 years, above- and below-ground biomass accumulation averaged about 1770 kg ha^{-1} $year^{-1}$ for trees evenly spaced at 6 m. By the age of 18 years, the average tree accumulates about 945, 38 and 420 g of N, P and K, respectively (Deans *et al.,* 1999).

Medicine

Gum arabic has therapeutic benefits in some diseases such as kidney and liver diseases and gastrointestinal illnesses (Ali *et al.*, 2009; Kadam *et al.,* 2019). Roots of *Acacia senegal* are used to treat dysentery, gonorrhea and nodular leprosy, whereas pods are effective free radical scavenger and chain breaking antioxidant (Marwah *et al.*, 2007; Pal *et al.,* 2012). Acacia fiber obtained from sap of the *Acacia senegal* tree is thought to help lower cholesterol levels, keep blood sugar in check and protect against diabetes, and aid in the treatment of digestive disorders (including irritable bowel syndrome). The soluble fiber dissolves in water and forms a gel-like substance in the intestines. In addition, acacia fiber is said to suppress appetite and support weight loss efforts, reduce inflammation, alleviate constipation, and relieve diarrhea. Seeds contain fat (khakhan), which is used for both medicine and for soap making (Azimova and Glushenkova, 2012).

Ecological Services

Erosion control

A. senegal plantations are used for controlling wind erosion and desertification, re-establishment of a vegetative cover in degraded areas, reclamation of mined land and sand dune fixation (Rao and tarfdar, 1998; Tewari *et al.,* 2007; Elhadi, 2009). Both surface feeding/spreading and anchoring roots help this species to adapt suitably and control desertification. The *rostrata* and *leiorhachis* varieties of *A. senegal* are useful for soil stabilization because of their weediness properties that reduce surface sand drift (Booth and Wickens, 1993). Along with providing vegetation cover, *A. senegal* binds soils by its extensive root system and reduce the extent of damage caused by wind and water erosion (Pasternak and Schlissel, 2001).

Nitrogen fixation and soil improvement

A. senegal and its different varieties show beneficial effects on soil fertility improvement through leaf fall, nitrogen fixation and microbial association which enhances herbage productivity in the rangelands and also improve crop productivity in agroforestry systems (Basak and Goyal, 1975; Abaker *et al.*, 2018; Bakhoum *et al.,* 2018). Though nitrogen fixation in *A. sengal* is questioned in some studies (MacDicken, 1994; Raddad *et al.,* 2005; Kumari, 2013), but Githae *et al.* (2013) estimated N-fixation in three *A. senegal* varieties (*A. senegal* var. *senegal*, *kerensis*, and *leiorhachis*) growing naturally in the drylands, in which *Balanites* *aegyptiaca* was selected as the reference species growing in the same area. Results showed that leaf ^{15}N natural abundance values ($\delta^{15}N$) differed between *A. senegal* and *B. aegyptiaca*. These values averaged 6.35, 4.67, and 3.03% for *A. senegal* var. *kerensis*, *leiorhachis*, and *senegal*, respectively, and were lower than those of the adjacent reference species. There were also significant differences in the amount of N_2 fixed among the varieties. *A. senegal* var. *senegal* showed the highest levels of N_2 fixation with a mean of 36%, while *A. senegal* var. *kerensis* and *leiorhachis* had equal estimates of 25%. However, no nodules were observed in the collected soil samples. Leaf N values differed significantly among the varieties with a mean of 2.73, 2.46, and 4.03% for *A. senegal* var. *kerensis*, *leiorhachis*, and *senegal*, respectively. This shows that *A. senegal* is able to fix N_2 in their natural ecosystems and can be utilized as plantations in agriculture and land rehabilitation programs.

Carbon sequestration

Acacia senegal improves fallows and contribute to the regeneration of degraded soils. It is one of the most abundant species in Africa. North Region of Cameroon has about 97% individuals of this species and shows 80.17 tons C ha^{-1} in the 7- 11years old fallows, 101.10 t C ha^{-1} in fallows of 12-16 years and 103.96 t C ha^{-1} in those over 17 years old. In soils, carbon stocks ranges from 67.78 t C ha^{-1} to 89.24 t C ha^{-1} (Temgoua *et al.,* 2018). In a study conducted on the C stocks in biomass and soil in *Acacia senegal* plantations of varying age (7-24 years) and adjacent open grasslands in two locations in Sudan (Abaker *et al.,* 2016), the total biomass C stock increased with plantation age, reaching to 1020 g m^{-2}. Carbon stock of the ground vegetation also increased with plantation age and was greater in the oldest plantations than in the open grassland. This indicates that *A. senegal* trees facilitate ground vegetation in semi-arid environments. The SOC stocks (0-50 cm) ranged from 846 to 1250 g m^{-2} and increased with age and were greater in plantation area than the open grassland (867-950 g m^{-2}). The SOC sequestration rate is 19 g C m^{-2} yr^{-1} in the oldest plantations. Studies at ICAR–CAFRI, Jhansi revealed that carbon sequestration by *A. senegal* increased with the age of plantation. After 7-years of planting *Acacia senegal* sequestered varying amount of carbon depending upon planting spacing or density (Figure 10). Maximum carbon stock was observed in plants grown under 5x5m spacing and minimum in 10x10m spacing. On an average 7-years old *A. senegal* sequestered 5.56 t ha^{-1} carbon at sequestration rate of 0.79 t $ha^{-1}year^{-1}$.

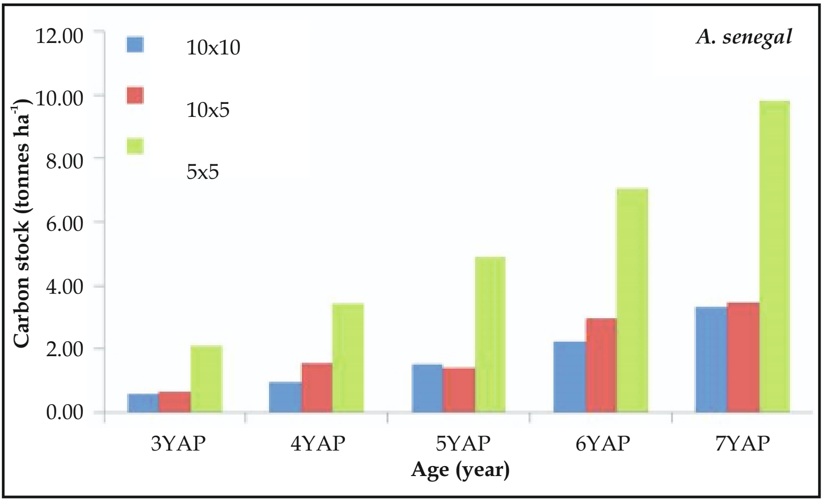


Figure 10. Effect of age and planting spacing on carbon sequestration by *A. senegal* in Bundelkhand

Chapter 9 Summary of Essentials and Way Forward

Acacia senegal (*Senegalia senegal*) is a multipurpose and economically important tree species of dry region. Popularly it is referred as gum arabic tree due to its most valuable natural exude called gum arabic. It can grow well in areas with less annual rainfall of 100-250mm. It is widely distributed throughout the arid and semi-arid parts of Africa, Australia, South Africa, Egypt, India, Pakistan and Virgin Islands of US. Because of its wide occurrence across the globe, there exist a large scale genetic variability in germplasms and also in morphological traits. It regenerates naturally, however, for establishing large scale man-made plantations and/or gum gardens, the artificial regeneration using seeds in nursery for raising planting stock is the common practice.

Acacia senegal is one of the most commercially exploited multipurpose trees and planted more frequently in Africa to support dryland ecosystems. From the point of view of agroforestry, volume of research has been done on evaluating *A. senegal* for its growth, biomass production, yield of gum arabic, compatibility in agroforestry systems and its potential to provide resilience against climate related risks of failing mono-cropping system in agriculture and securing alternate means of sustenance. Present synthesis in the form of a monograph on *A. senegal* focuses on integration of this unique gum-yielding tree species in agroforestry on farmlands with special reference to semi-arid region of central India. Depending on the site conditions, different types of agroforestry models *viz.* gum-garden as block plantation in degraded rocky sites, agri-silviculture and lemon grass based silvi-herbal model for rainfed area, and multi-component based agri-horti-silvicultre model for irrigated area have been recommended. Besides, bio-fence model with double-row staggered planting of *A. senegal* and/or *A. senegal*+*C. caradas* may prove a boon in protecting agricultural crops from stray cattle (*anna pratha*). Benefit: cost analysis of multi-component based agri-horti-silvicultre revealed that this agroforestry model can offer income of Rs. 127284 ha^{-1} for an investment of Rs. 59126 ha^{-1} with B:C ratio of 2.15 after 10 years. Further, early and regular returns from woody/fruit components exhibited potential of the model to provide resilience against climate related risks by acting as a sink for failure of agricultural crops. *Acacia* *senegal* based agroforestry practice on farmland holds a great future in arid and semi-arid regions.

Despite wide occurrence of *A. senegal* in Indian subcontinent particularly in arid and semi-arid regions, the full potential of this tree has not been realized. Upscaling *A. senegal* on farmland in the form of agroforestry appears to be the only approach by which the production base of gum arabic can be enhanced which, in turn, will reverse the declining trend of gum arabic production in India. Poor productivity of gum arabic, due to over exploitation of limited resource base, is affecting national and international trade adversely.

Development of *Acacia senegal* horizontally by increasing its area under agroforestry and vertically by innovative research that can provide scientific support and motivate farmers for its adoption on farmland in different site conditions, can bring boom in the dwindling gum industry and sustainability in agricultural production system. Following are some of the areas wherein extension agencies and researchers need to focus in future:

- The gum trade depends on fluctuations in supplies and often disrupted trade looks for alternatives and if, they are available, the demand of gum arabic is likely to reduce further in international trade. There is need to assess various aspects of gum arabic trade in national and international arena. Developing nation like India can take advantage of disrupted trade by raising large scale plantations of *A. senegal* and increase its share in the trade by enhanced gum production.
- There is a need for identification and utilization of best strains of *A. senegal* for improved growth and gum production. Successful development of vegetative methods of propagation of *A. senegal* would enhance selection and breeding of aimed high gum yielding genotypes. Also, in depth research is needed to study tree-to-tree, site-to-site and seasonal variation in quality of exuded gum. The longevity of rotation in various plantation systems for production of gum needs to be standardized.
- *A. senegal* has exhibited its potential for integration in agroforestry systems on farmlands and silvi-pastoral systems on rocky and gravely hilly areas including rangelands in semi-arid region of Bundelkhand. Hence, *A. senegal* need to be included in State Forest Plantation Programmes and in agroforestry projects being implemented in the semi-arid Central India, as the region offers

good scope and suitable conditions for its establishment and growth. The state of Rajasthan has also included *Acacia senegal* in their afforestation program and planted lakhs of seedlings in western Rajasthan.

- Availability of soil moisture and nutrients in soil increases gummosis and hence, raising plantation of improved strain of this species in degraded lands including community and forest lands, coupling with moisture conservation measures and effective nutrient management needs to be standardized. Detailed studies are required on management of soil and plant nutrition for equilibration of energy to harness maximum gum productivity from commercial plantations.
- There is a need to develop standard protocol of gum tapping so that maximum gum can be obtained with minimum harm to the trees. This is to be twined with the value addition for scoping gum-arabic for socio-economic benefits by systematic linkage with the market.
- Involvement of village community in raising quality planting material for plantation, protection and management of *A. senegal* may add value to livelihood options.
- Systematic research is required on biology and ecology of harmful insects and pathogens for effective control measures. Similarly, toxicity developed during storage of seeds to be used as food material needs to be investigated for corrective measures.

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