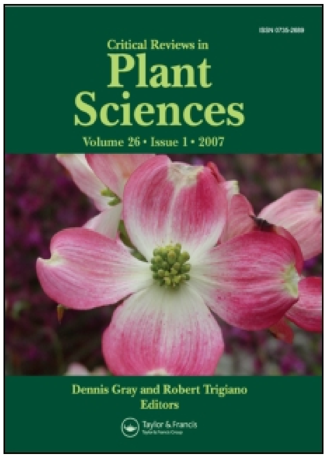

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S. J. H. Rizvi [ab]; M. Tahir [c]; V. Rizvi [ab]; R. K. Kohli [d]; A. Ansari [a]
[a] Plant Pests and Diseases Research Institute, P.O. Box 19395-1454, Evin, Tabnak Av., Tehran, Iran.
[b] Permanent address: Faculty of Basic Sciences, Rajendra Agricultural University, Pusa-848125, Samastipur, India.
[c] International Center for Agricultural Research in Dry Areas (ICARDA) Regional Office, Agricultural Research, Education and Extension Organization, P.O. Box 19835-111, Tehran, Iran.
[d] Department of Botany, Panjab University, Chandigarh, India.

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Allelopathic Interactions in Agroforestry Systems

S. J. H. Rizvi,[1,2] M. Tahir,[3] V. Rizvi,[1,2] R. K. Kohli,[4] and A. Ansari[1]*

[1]Plant Pests and Diseases Research Institute, P.O. Box 19395–1454, Evin, Tabnak Av., Tehran, Iran; [2]Permanent address: Faculty of Basic Sciences, Rajendra Agricultural University, Pusa-848125, Samastipur, India; [3]International Center for Agricultural Research in Dry Areas (ICARDA) Regional Office, Agricultural Research, Education and Extension Organization, P.O. Box 19835–111, Tehran, Iran; [4]Department of Botany, Panjab University, Chandigarh, India

* Corresponding author.

ABSTRACT: Agroforestry is a modern tool to develop sustainable land use and to increase food production by growing woody species (trees, shrubs, palms, bamboos, etc.) with agricultural crops and/or animals in some form of spatial arrangement or temporal sequence. Because these species co-exist with the agricultural crops, their allelopathic compatibility may be crucial to determine the success of an agroforestry system. A survey of the available information reveals that most of the agroforestry species (AF species) have negative allelopathic effects on food and fodder crops. Therefore, it is desirable to do further research in this direction so that AF species with no or positive allelopathic effects on the companion crops may be promoted for agroforestry programs. As AF species remain a part of the agroecosystem for a longer period, and most of them produce a large amount of leaves and litter, their allelochemicals may play an important role in developing an eco-friendly pest management strategy. Besides these generally studied aspects of allelopathy, some comparatively newer aspects of research have been identified, such as evaluation of qualitative yield of agroforestry systems, selective behavior of the allelochemicals, effect on soil quality, and the role of tree allelochemicals in animal and human nutrition. If given due consideration, allelopathy could play a pivotal role in conservation of the highly threatened environment, biodiversity, natural resource base, and making agriculture more sustainable through broadening the scope of agroforestry.

KEY WORDS: agroforestry, allelochemicals, allelopathy, eco-friendly pest control, qualitative yield.

I. INTRODUCTION

Agroforestry is a sustainable land management system that increases the yield of the land, combines the production of crops (including tree crops) and forest plants, and/or animals simultaneously or sequentially on the same unit of land, and applies management practices that are compatible with the cultural practices of the local population (Bene et al., 1977; King and Chandler, 1978). It is evident that the pioneers in "agroforestry" considered that the ultimate objective of the system was not tree production but food production in totality. Further, development of the agroforestry system was considered a means of sustainable land use to cope with the magnitude and the rate of the world population growth, hunger, and worldwide environmental degradation. Unfortunately, by the end of nineteenth century the establishment of forest plantations had become the dominant objective of agroforestry. Landless laborers were employed with a provision that they can cultivate the land left between the rows of forest trees and use the agricultural products. However, the priority for forest trees always controlled the agricultural operations in a way that the interests of forestry should not be compromised (King, 1968). This philosophy created a serious problem especially in the less-developed countries because development of forest and forest industry debarred the local people from basic forest products. Thus, the most important role of forestry, that is, to support agriculture and rural welfare was almost totally ignored (Westoby, 1975).

Such realization coupled with other socioeconomic pressures resulted in reassessment and reexamination of developmental policies by agencies like the World Bank and Food and Agriculture Organization (FAO). This led the International Development Research Center (IDRC) to commission a project under the leadership of John Bene to identify the priorities for tropical forestry research. FAO focused its attention toward the rural poor and emphasized the importance of forestry for rural development. During 1976 to 1978 a series of seminars and workshops was held and as a result agroforestry was identified as a system to provide food, fuel, fodder, and other useful products in a sustainable manner. However, the formal rediscovery of agroforestry by the global scientific community can be credited to Bene and his group and the IDRC. Bene and his associates recommended that the priority should be given to combining production systems, which would integrate forestry, agriculture, and/or animal husbandry in order to optimize land use (Bene et al., 1977). Finally, with the establishment of the International Center for Research in Agroforestry (ICRAF), one of the oldest integrated traditional land use systems was transformed into a scientific discipline called agroforestry. Presently, one of its most widely accepted scientific definition is,

> Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In the agroforestry system there are both ecological and economical interactions between the different components
>
> (Lundgren and Raintree, 1982)

Agroforestry is being practiced in a variety of climatic conditions to achieve one or more goals, and thus needs a classification. Some of the commonly employed criteria for classification are based on arrangement of different components of the system (spatial/temporal), relative importance and role of various components, production aims, and social/economic features. On the basis of components, it is mainly divided into agriculture (crops-trees-shrubs-vines), silvopastoral (pasture-animals-trees), and agrisilviculture (crops-pasture-animals-aquaculture-sericulture-apiculture-trees). Based on the space arrangement, it can be divided into mixed dense, mixed sparse, support tree, etc. When classified from the viewpoint of protection, agroforestry is divided into soil conservation, moisture conservation, shelterbelts, and windbreaks. However, when the emphasis is on production, it is divided into food, fodder, timber, etc. Recently, attention has been paid to the possible allelopathic interactions between different components of the agroforestry system to make it more productive and sustainable (Rizvi et al., 1992). We intend to discuss here the problems and prospects of such interactions.

II. ALLELOPATHY IN AGROFORESTRY SPECIES

Owing to a worldwide awareness about the benefits and potential of agroforestry, extensive research has been conducted in this area in a relatively short period. Some of the best known positive points about agroforestry are an overall increased productivity (Avery et al., 1991; Burch and Parker, 1992), enrichment of soil with organic matter and nitrogen (Agboole and Fayemi, 1975; Ta and Farris, 1988), transport of nutrients from lower to the upper layer of soil (Yamoah et al., 1986), conservation of environment (Turnbull, 1984; Baumer, 1990), improved microclimate (Harris and Natarajan, 1987), and rural development through employment generation (Chambers, 1983).

To optimize the gains of agroforestry, several standard management practices have been evolved and selection of suitable agroforestry species (AF species*) is one of those. Any such selection is based on a number of important characters of AF species, such as fast growth rate, thorough pas-

* The term agroforestry species (AF species) covers all kinds of woody perennial trees, shrubs, palms, and bamboos grown with annual crops in agroforestry systems.

sage for sunlight to the ground, rooting pattern, and multipurposeness of AF species. It is surprising that allelopathic properties of AF species so far have not been paid due attention. Research in this area began in the 1980s (Kuo et al., 1983; Melkania, 1984; Rizvi and Rizvi, 1987), but the surface has only been scratched. Detailed information about the allelopathic effects of AF species on other components (annual plants) of agroforestry systems is limited. If available, such information would prove useful to identify 'allelopathically compatible' AF species (having either beneficial or at least no adverse effect on companion crop) or 'noncompatible' ones with inhibitory effects. This kind of knowledge would greatly facilitate formulation of agroforestry systems with higher yields by avoiding harmful allelopathic interactions and through exploitation of beneficial effects of particular AF species. Information available on allelopathic activities of some of the important AF species is summarized in Table 1. All the AF species (except *Moringa oleifera)* tested for allelopathic activity have shown an inhibitory effect on crop plants.

III. TREE ALLELOPATHY: SOME EXAMPLES

A. *Azadirachta indica*

Azadirachta indica (commonly known as neem) is a tree that has been used for centuries for medicinal and pesticidal properties. The tree is indigenous to the Indian subcontinent, but it has been introduced and promoted in other regions of the world. With the onset of agroforestry research, new frontiers for its exploitation have been discovered besides its traditional uses in pest control, toiletries, pharmaceutical, cosmetics, plant and animal nutrition, industry, and energy generation. Owing to its enormous uses, the U.S. National Academy of Sciences has recognized it as a tree for solving global problems (Anon., 1992). However, results of some agroforestry trials indicate its possible allelopathic effects on companion crops. Hazra and Tripathi (1989) have reported that under semi-arid conditions, forage yield of oats (*Avena sativa*) was 26% less under neem tree than in open plots. Similarly, the reduction in crop yields due to neem trees varies from 7 to 33% in sorghum (*Sorghum bicolor*), and 3 to 16% in safflower (*Carthamus* sp.) (Srivastava and Rammohanrao, 1989). Further studies, however, suggest a selective effect of neem tree. Puri and Bangawa (1992) have found that neem tree has no adverse effect on the yield of wheat (*Triticum aestivum*) if grown 5 m apart from the main stem. Some studies suggest a direct role of neem allelochemicals in this effect on crop plants. Melkania (1984) found inhibition of germination of seeds of barnyard grass (*Echinochloa crus-galli*), buckwheat (*Fagopyrum sagittatum*), soybean (*Glycine max*), and turnip (*Brassica rapa*) by leachates of leaf, wood, and leaf litter. Maize (*Zea mays*), mustard (*Brassica campestris*), pea (*Pisum sativum*), and wheat germination was also inhibited by litter extract (Joshi and Prakash, 1992). The extracts were particularly inhibitory to the root growth (Alam, 1990). Although a number of biologically active chemicals have been isolated and identified, a correlation is yet to be established between their presence and allelopathic properties of neem.

B. *Eucalyptus* spp.

Eucalyptus has been promoted on a large scale in various parts of the world. This is because of its fast growth, adaptability to various edaphic and climatic conditions, lesser soil coverage, least post-plantation care, and above all the industrial value. However, its indiscriminate promotion without giving any significance to edaphic and ecological stability has evoked concern among environmentalists. In fact, during the last decade it has suffered from a dramatic fall in popularity because of its antiphytosocial nature (Kohli, 1987) and ill effects on the ecology (Poore and Fries, 1985). Its monoculture plantations are reported to support either very little or almost negligible understorey vegetation (del Moral and Muller, 1969; del Moral et al., 1978; Bhaskar and Dasappa, 1986; Singh et al., 1993). The species diversity index is also highly reduced under eucalypt monoculture plantations when compared with the other native plantations. Allelopathy has often been considered as

TABLE 1
Allelopathic Activity of Some Agroforestry Species

Agroforestry species	Target species	Plant parts/ allelochemicals	Uses of agroforestry species	Ref.
Abies alba	*Abies alba* *Lepidium sativum* *Picea abies* *Pinus sylvestris*	Natural leachate, aqueous extracts of fresh needles and seeds	Fuel wood	Becker and Drapier, 1984 ,85 Georgiev, 1983
Acacia arabia	*Triticum aestivum* *Pyricularia oryzae*	Canopy effect, extracts of various parts	Building material/fuel wood/ farm timber/pest control	Prakash et al., 1989 Sheikh and Haq, 1978
A. auriculiformis	*Cicer arietinum* *Oryza sativa* *Triticum aestivum*	Aqueous leaf leachate	Aforestation	Jadhav and Gaynar, 1992 Rao et al., 1994
A. confusa	*Bidens bipinnata* *Brassica chinensis* *Lactuca sativa*	Aqueous leachates and extracts of fresh and dried leaves, leaf litter, seed/pod extract	Aforestation	Kuo et al., 1989
A. cyclops	*Eriocephalus racemosus* and several other non-crop plants	Aqueous extract of of phyllode	Aforestation	Rutherford and Powrie, 1993
A. dealbata	*Lolium perenne* *Trifolium pratense* *T. repens*	Aqueous extracts of leaves, flowers, and soil	Aforestation	Casal et al., 1985
A. excelsa	*Casuarina equisetifolia*	Aqueous extract of mature leaves	Shade	Balasubramanian and Ravichandran, 1996
A. leucopholea	*Cajanus cajan* *Sesamum indicum* *Zea mays*	Bark leachate	Multipurpose tree (MPT)	Swaminathan, 1996
A. mangium	*Shorea leprosula* *S. stenoptera*	Soil	Timber	Anwar, 1992
A. melanoxylon	*Lactuca sativa*	Phyllode extract	Aforestation	Gonzalez et al., 1995
A. nilotica	*Casuarina equisetifolia* *Cajanus cajan* *Sesamum indicum* *Rhizobium* sp. *Zea mays*	Aqueous extract of mature leaves, bark leachate	Beverage/fuel wood/MPT	Balasubramanian and Ravichandran, 1996 Duhan et al., 1994 Swaminathan, 1996
A. tortilis	*Cicer arietinum* *Gossypium hirsutum* *Trifolium alexandrum* *Triticum aestivum*	Aqueous extracts of fresh leaves and roots, soil from under canopy	Fodder/fuel wood	Saxena and Sharma, 1996
A. xanthopholea	*A. xanthopholea* *Albizia lebbek* *Vigna radiata* *Zea mays*	Leaf and bark litter leachates	Fodder/fuel wood	Nsolomo et al., 1995
Adhathoda vasica	*Brassica campestris* *Triticum vulgare* *Zea mays*	Aqueous extract, rain leachate, litter, soil	Live fences/soil conservation	Ayaz et al., 1989
Aegle marmelos	*Sclerotonia sclerotirum*	Leachates of roots, seed, and bark	Fruit/timber/medicinal use/ pathogen control	Ram, 1989
Albizia lebbek	*Oryza sativa* *Parthenium hysterophorus*	Canopy effect Aqueous extract of leaves	Fuel/fodder	Bhatt et al., 1997 Dhawan and Dhawan, 1995
A. stipulata	*Eleusine coracana* *Echinochloa colonum* *Phaseolus radiata* *Lens esculentus*	Aqueous extracts of green leaves, leaf litter, and bark	Fuel/fodder/land rehabilitation/nitrogen fixation	Uniyal and Nautiyal, 1996
Annona squamosa	*Amaranthus spinosus*	Ethanolic extracts of leaves and seeds	Food/fuel wood	Rizvi et al., 1980b
Azadirachta indica	*Fagopyrum* sp., *Glycine max, Oryza sativa, Pisum sativum Triticum aestivum, Zea mays,* a number of microorganisms	Leaf, wood and leaf litter leachates, litter, and mature leaf extracts	Timber/lumber/manure/oil/ fuel/food/pest control	Joshi and Prakash, 1992 Melkania, 1984 Rao et al., 1994 Schmutterer, 1995a
Bambusa arundinacea	*Arachis hypogea*	Aqueous leaf extract	Building material/domestic uses/fence	Eyini et al., 1989
B. indica	*Costus speciosus*	Leaf leachate	Building material/domestic uses/fence	Konar, 1996
Bauhinia variegata	*Vigna unguiculata,* Zea mays	Leachates of leaves and naturally flaked bark	Food/fuel wood	Kaletha et al., 1996

TABLE 1 (continued)
Allelopathic Activity of Some Agroforestry Species

Agroforestry species	Target species	Plant parts/ allelochemicals	Uses of agroforestry species	Ref.
Camellia sinensis	*C. sinensis*	Purine alkaloids in seeds	Beverages	Suzuki and Waller, 1987
Carica papaya	*Amaranthus spinosus*	Ethanolic extracts of leaves and seeds	Food/fruit/shade	Rizvi et al., 1980b
Casuarina equisetefolia	*Cajanus cajan* *Helianthus annuus* *Sorghum bicolor* *Zea mays*	Leaf mulch, top soil, bark leachate	Charcoal/fuelwood/timber	Suresh and Vianaya Rai, 1987 Swaminathan, 1996
Celtis australis	*Brassica campestris* *Glycine max* *Hordeum vulgare* *Lepidium sativum*	Soil, dry leaf mulch, aqueous leaf extract and leachate	Food/fuelwood/timber	Bhatt and Todaria, 1990 Melkania, 1992
Citrus aurantium	*Amaranthus retroflexus* *Avena sativa* *Chenopodium album* *Citrus aurantium* *Cynodon dactylon*	Aqueous leaf extract, decaying material	Essential oils/food	Al-Saadawi and Al-Rubeaa, 1985 Al-Saadawi et al., 1985 Hassan et al.,1989
Citrus sinensis	*Citrus sinensis*	Soil from old orchards	Food/shade/firewood/fruit	Hassan et al., 1989
Coffea arabica	*Amaranthus spinosus* *Coffea arabica* *Lactuca sativa* *Secale cereale*	Aqueous/ethanolic extract, caffeine, paraxanthine, scopoletin, theobromine, theophylline, and phenolic acids	Beverage/fuel wood/food	Chou and Waller, 1980 Evenari, 1949 Friedman and Waller, 1983 Rizvi and Rizvi, 1984, 1992b, Rizvi et al., 1987
Dalbergia sissoo	*Cicer arietinum* *Oryza sativa* *Triticum aestivum*	Soil, exudates, mature leaf extract	Shade/timber poles	Puri and Bangawa, 1992 Rao et al., 1994
Emblica officinalis	*Pyricularia oryzae*	Extracts of various parts	Fruit/pest control	Prakash et al., 1989
Eucalyptus sp.	*Acacia saligna* *Lemna minor* *Lolium perenne*	Shelterbelt effect	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990 Onyewotu, 1985
E. alba	*Shorea palembanica* *Zea mays*	Fresh leaves, leaf litter, root, and stem extracts	Lumber/firewood/stake/ timber/essential oil/pole	Anwar, 1991a,b
E. baxteri	*Casuarina pusilla* *Leptospermum viminalis* *Triticum aestivum*	Soil, topsoil extract, foliar, and litter leachates	Lumber/firewood/stake/ timber/essential oil/pole	del Moral et al., 1978
E. blakelyi	*Lemna minor*	Soil-decomposing litter	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990
E. camaldulensis	*Abelmoschus escutentus* *Amaranthus caudatus* *Avena fatua* *Bromus mollis* *Bromus rigidus* *Cicer arietinum* *Vigna radiata* *Zea mays*	Leachates and aqueous extracts of dried/fresh leaves, bark, leaf litter, volatiles, soil, 1,8-cineole, α-pinene, α-phellandrene, phenolic, gallic, and ferulic acids	Lumber/firewood/stake/ timber/essential oil/pole	del Moral and Muller, 1970 Igboanugo, 1986 Jensen, 1983 Lisanework and Michelsen, 1993 Mizutani, 1989
E. citriodora	*Avena sativa* *Capsicum annuum* *Helianthus annuus* *Hordeum vulgare* *Lens esculentum* *Lycopersicon esculentum* *Zea mays*	Aqueous extract of fresh leaf litter, leaf leachate, crude volatile oils, oil adsorbed soil, canopy effect	Lumber/firewood/stake/ timber/essential oil/pole	Igboanugo, 1986, 1988a,b Kohli and Singh, 1991 Singh et al., 1991 Vicherková and Polová, 1986
E. delegatensis	*E. delegatensis*	Aqueous extracts of roots and leaves, leachate of chopped leaves	Lumber/firewood/stake/ timber/essential oil/pole	Bowman and Kirpatrick, 1986
E. deglupta	*Shorea palembanica* *Zea mays*	Fresh leaves, leaf litter, stem flow	Lumber/firewood/stake/ timber/essential oil/pole	Anwar, 1991a,b
E. elata	*Lemna minor*	Decomposing litter, soil	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990
E. globulus	*Cicer arietinum* *Cucumis sativus* *Glaucium flavum* *Phaseolus aureus* *Lactuca sativa*	Leaf extract and leachate, essential oils, oils, soil percolate, canopy effect	Lumber/firewood/stake/ timber/essential oil/pole	Baker, 1966 del Moral and Muller, 1969 Kohli and Singh, 1991 Molina et al., 1991 Singh and Bawa, 1982 Singh et al., 1991
E. grandis	*Abelmoschus esculentus* *Amaranthus caudatus*	Decomposing plant parts	Lumber/firewood/stake/ timber/essential oil/pole	Igboanugo, 1987

TABLE 1 (continued)
Allelopathic Activity of Some Agroforestry Species

Agroforestry species	Target species	Plant parts/ allelochemicals	Uses of agroforestry species	Ref.
E. macrorrhyncha	*Lemna minor* *Lolium perenne* *Raphanus sativus* *Triticum aestivum*	Leaf and bark litter leachates, stem flow	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990 Nayyar et al., 1994
E. maculata	*Lemna minor*	Leaf and bark litter leachates	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990 Nayyar et al., 1994
E. mannifera	*Lemna minor*	Decomposing litter, soil	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990 Nayyar et al., 1994
E. melliodora	*Lemna minor*	Decomposing litter, soil	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990 Nayyar et al., 1994
E. microtheca	Herbaceous species	Phytotoxins	Lumber/firewood/stake/ timber/essential oil/pole	Al-Mousawi and Al-Naib, 1975, 1976
E. polyanthemosa	*Lemna minor*	Decomposing litter, soil	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990 Nayyar et al., 1994
E. pulverulenta	*Lipidium sativum*	Grandinol	Lumber/firewood/stake/ timber/essential oil/pole	Bolte et al., 1984
E. radiata	*Lemna minor*	Volatile substances	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990 Nayyar et al., 1994
E. robusta	*Zea mays*	Fresh leaves, leaf litter, stem flow	Lumber/firewood/stake/ timber/essential oil/pole	Anwar, 1991a
E. rossii	*Lemna minor* *Lolium perenne*	Stem flow, bark and leaf litter leachates	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990
E. rubida	*Acacia saligna* *Eucalyptus globulus* *Lemna minor* *Lolium perenne*	Leaf and bark litter leachates, decomposing litter, soil	Lumber/firewood/stake/ timber/essential oil/pole	May and Ash, 1990
E. saligna	*Cicer arietinum* *Eragrostis* sp. *Pisum sativum* *Zea mays*	Aqueous leaf extract	Lumber/firewood/stake/ timber/essential oil/pole	Lisanework and Michelsen, 1993
E. tereticornis	*Brassica* spp. *Cicer arietinum* *Helianthus annuus* *Lens esculentum* *Nigella sativa* *Phaseolus mungo* *Setaria italica* *Sorghum vulgare* *Triticum aestivum*	Leaf and flower extracts, leaf litter and mulch, canopy effect, shelterbelt effect	Lumber/firewood/stake/ timber/essential oil/pole	Ahmad et al., 1984 Bhaskar and Dassappa, 1986 Sidhu and Hans, 1988 Singh and Kohli, 1992 Suresh and Vinaya Rai, 1987, 1988
Ficus bengalensis	*Brassica campestris* *Lens culinaris* *Phaseolus vulgaris* *Raphanus sativus* *Triticum aestivum* *Zea mays*	Aqueous leaf extract, litter, soil	Charcoal/food/fuelwood/ beverage/shade/soil conservation	Akram et al., 1990
F. palmata	*Trifolium alexandrum* *Zea mays*	Aqueous leaf extract, litter, soil	Charcoal/food/fuelwood/ beverage/shade/soil conservation	Akram et al., 1990
F. racemosa	*Brassica campestris* *Lens culinaris* *Phaseolus vulgaris* *Raphanus sativus* *Triticum aestivum* *Zea mays*	Aqueous leaf extract, litter, soil	Charcoal/food/fuelwood/ beverage/shade/soil conservation	Akram et al., 1990
		Aqueous leaf extract, litter, soil	Charcoal/food/fuelwood/ beverage/shade/soil conservation	Akram et al., 1990
F. religiosa	*Brassica campestris* *Lens culiraris* *Phaseolus vulgaris* *Raphanus sativus* *Triticum aestivum* *Zea mays*	Aqueous leaf extract, litter, soil	Charcoal/food/fuelwood/ beverage/shade/soil conservation	Akram et al., 1990
F. roxburghii	*Vigna unguiculata* ***Zea mays***	Leaf, naturally flaked bark	Charcoal/food/fuelwood/ beverage/shade/soil conservation	Kaletha et al.,1996

TABLE 1 (continued)
Allelopathic Activity of Some Agroforestry Species

Agroforestry species	Target species	Plant parts/ allelochemicals	Uses of agroforestry species	Ref.
Fraxinus micrantha	*Brassica campestris* *Raphanus sativus* *Triticum aestivum*	Aqueous leaf extract, coumarins	Timber	Joshi et al., 1996
Gliricidia maculata	*Helianthus annuus* *Oryza sativa* *Phaseolus mungo* *Vigna radiata*	Leaf aqueous extract	Shade/soil fertility	Patil, 1994
G. sepium	*Bidens pilosa* *Lycopersicon esculentum*	Leaf and bark (root) extracts, protocatechuic acid, canavanine	Crop shade/food/fuel wood/ live fence/poles/shade	Inostrosa and Founier, 1982
Gmelina arborea	*Zea mays*	Leaf	Firewood/lumber/shade/ food/building material	Hauser, 1993
Grewia optiva	*Brassica campestris* *Fagopyrum esculentum* *Glycine soja* *Lepidium sativum* *Setaria italica*	Leaf leachate	Food/shade/wind break/soil conservation	Melkania, 1984
Grevillea robusta	*Grevillea robusta*	Aqueous root extract	Food/fuelwood/tools, and utensils	Webb et al., 1967
Inga edulis	*Oryza sativa*	Soil, exudate	Crop shade/food/soil conservation	Salazar et al., 1993
Leucaena leucocephala	*Acacia confusa* *A. nilotica* *Ageratum conyzoides* *Alnus formosana* *Lactuca sativa* *Oryza sativa* *Sorghum bicolor* *Vigna radiata* *V. mungo*	Aqueous leachate/ extracts of leaves, litter, soil, dry leaf mulch, topsoil Mimosine, *p*-hydroxy-phenylacetic acid, *cis*- and *trans*-*p*-hydroxycinnamic acid, *p*-hydroxybenzoic acid, sinapic acid, vanillic acid, caffeic acid, *p*-coumaric acid, quercetin	Fuelwood/pole/timber/food/ soil conservation/fodder	Chaturvedi and Jha, 1992 Chou and Kuo, 1986 Kuo et al., 1983 Prasad and Subhashini, 1994 Rizvi et al., 1990a,b
Melia azadirach	*Brassica campestris* *Lepidium sativum* *Raphanus sativus* *Setaria italica* A number of microorganisms	Leaf leachate	Crop shade/fuel wood/ timber/lumber	Melkania, 1984
Moringa oleifera	*Oryza sativa* *Vigna mungo*	Leachate of intact and chopped leaves, soil mixing of leaves	Fruit/vegetable/medicinal value	Rizvi and Rizvi, 1996
Pinus radiata	*P. radiata* *Rhizopogon* sp. *Secale cereale* *Trifolium repense*	Volatile substances, soil, root extract	Pulp/timber mulch	Lill and McWha, 1976
Populus deltoides	*Saccharum officinarium* *Triticum aestivum*	Soil, leachate	Timber	Ralhan et al., 1992 Sheikh and Haq, 1986 Singh et al., 1993
Prosopis cineraria	*Triticum aestivum*	Soil, leachate	Shade/soil conservation/ wind break	Puri and Bangawa, 1992
P. juliflora	*P. juliflora* *Sorghum bicolor* *Vigna mungo*	Leaf, stem, litter, and soil leachates	Fodder/fire wood/shade	Chellahmuthu et al., 1997 Sundarammorthy et al., 1995 Warrag, 1995
Prunus cerasoides	*Eleusine coracana* *Glycine max* *Hordeum vulgare*	Soil, dry leaf mulch, aqueous leaf extract	Food/fuel wood/timber	Bhatt and Todaria, 1990
P. jacquemontii	*Raphanus sativus*	Root extract	Food/fuel wood/timber	Joshi et al., 1997
Psidium guajava	*Lactuca sativa* *Setaria verticillata*	Living root exudate, alcohol extract of dried roots	Fruit/fuel wood/tools	Brown et al., 1983
Ricinus communis	*Meloidogyne incognita* *M. javanica*	Oil cake	Pest control/medicinal value	Alam and Khan, 1974 Singh, 1969

TABLE 1 (continued)
Allelopathic Activity of Some Agroforestry Species

Agroforestry species	Target species	Plant parts/ allelochemicals	Uses of agroforestry species	Ref.
Tamarindus indica	*Amaranthus spinosus*	Ethanolic extracts of leaves and seeds	Beverage/fruit/fuel wood/ food/shade/tools/rituals	Rizvi et al., 1980b
Tectona grandis	*Arachis hypogea* *Cajanus cajan* *Sesamum indicum* *Zea mays*	Extract of fallen leaves, bark leachate	Firewood/lumber/shade/ timber	Chaturvedi and Sharma, 1997 Jeyakumar et al., 1987 Swaminatham, 1996
Terminalia arjuna	*Cicer arietinum* *Oryza sativa* *Triticum aestivum*	Mature leaf extract	Building material/ timber/fuel	Rao et al., 1994
T. tomentosa	*Oryza sativa* *Vigna unguiculata*	Leaf leachate	Building material/timber/ fuel wood	Gaynar and Jadhav, 1992
Vitex negundo	*Andropogon nodosus* *Brassica chinensis* *Digitaria decumbens* *Mimosa pudica* *Secale cereale* A number of insects	Dried leaf extract, *p*-hydroxybenzoic, *p*-coumaric, ferulic, vanillic, syringic acids, flavonoids	Weed control/medicinal value	Chou and Yao, 1983 Kuo et al., 1989

a possible reason for the species depletion (Suresh and Vinaya Rai, 1987; Kohli et al., 1992).

Eucalypt species have been used as a favorable AF species. These are usually planted on the field boundaries as windbreaks, shelterbelts, or simply scattered in the fields. Studies have shown that the shelterbelts of eucalypts are very harmful to the crops growing in the adjoining area (Jensen, 1983; Onyewotu, 1985; Igbuanugo, 1988a,b; Kohli 1990; Malik and Sharma, 1990; Puri and Bangawa, 1992; Singh and Kohli, 1992). Kohli and his associates have reported significant reduction in the density, root and shoot length, biomass, and economic yield of crops up to 11 m from the shelterbelts of *Eucalyptus*. They suggested that the performance of the crops can be assessed by a mathematical formula (% Performance = 100 + m (x-24)/2, where x represents distance from the tree and m represents value of regression slope). Later, based on the evaluation of bioefficacy of phytotoxins (extracted from the soil collected at different distances from the tree, and at various depth from the soil surface), the poor crop performance was attributed to the allelopathic property of *Eucalyptus* (Kohli et al., 1990; Singh and Kohli, 1992). It is desirable to conduct similar studies with other AF species.

Eucalypts are reported to release a number of volatile and nonvolatile allelochemicals that affect growth of the associated vegetation (Kohli, 1990). Various volatile terpenes like limonene, cineole, citronellal, citronellol, α-pinene, and grandinol, etc. identified from the crude oil are highly toxic and affect the germination and growth of native vegetation (Baker, 1966; del Moral and Muller, 1970; Al-Mousawi and Al-Naib 1975, 1976; Bolte et al., 1984; Kohli et al., 1992). Under natural conditions, volatile oils are released from the leaves through diffusion and being heavier than air, travel downward, get adsorbed to the surface of soil particles, and thus affect the vegetation supported by this soil. The content of the oil in leaves varies with species, climatic conditions, and because of seasonal changes.

The germination, seedling vigor, and seedling length of the four crops, namely, *Phaseolus aureus*, *Hordeum vulgare,* and *Avena sativa* were significantly reduced when placed in chambers flushed with eucalypt oil (Kohli and Singh, 1991). Further, when seeds of *P. aureus* were placed in Petri dishes having soil adsorbed with eucalypt oils, the germination was greatly reduced (Singh et al., 1991). The volatile allelochemicals have also been found to inhibit respiration (Vicherková and Polová, 1986), reduce the chlorophyll content, and cause wilting (Kohli and Singh, 1991). In addition, the leachates and extracts from the eucalypt leaves, litter, bark, flowers, and leaf mulch have been reported to reduce the germination and initial growth of a number of plant species (Singh and Bawa, 1982; Ahmed et al., 1984; Igboanugo, 1986; Sidhu and Hans, 1988; Kohli, 1990; May and Ash, 1990; Lisanework and Michelson, 1993). A number of agricultural crops were tested for their susceptibility or resistance to the aqueous leachates of *Eucalyptus*. Interestingly, the level of resistance was determined by the ratio of seed coat thickness and seed volume. The critical values of this ratio were determined mathematically, and it was found that seeds with a ratio of seed coat thickness to seed volume greater than 0.79 were resistant or the vice versa (Kohli, 1994).

Studies conducted by Kohli (1990) and Singh (1991) demonstrate that both volatile as well as nonvolatile allelochemicals are continuously being added to the soil system beneath the plantations. The soil collected from the floor of these plantations was found to be rich in phenolic compounds. Their content varied with distance as well as depth. Later, a number of phenolic acids like gallic acid, gentisic acid, syringic acid, vanillic acid, caffeic acid, *p*-coumaric acid, ferulic acid, and cinnamic acid were identified in the soil as well as in the leaves (Kohli, 1990).

C. *Leucaena leucocephala*

Leucaena is a widely recommended tree species for agroforestry because of its fast growth rate, fodder, fuel and wood value, ability to fix nitrogen, and to improve the overall productivity of land (Chou and Waller, 1989; Nair, 1989; Lantican and Taylor, 1991). However, the presence of a non-protein amino acid along with some phenolic compounds in its leaves and seeds is a cause of concern to allelopaths and ecologists.

Chou and his associates after working with different species of *Leucaena* for several years have concluded that exclusion of understorey vegetation by *Leucaena* is at least partly mediated by allelopathy (Kuo et al., 1983; Chou and Kuo, 1986; Chou, 1993). Suresh and Vinaya Rai (1987, 1988) tested the allelopathic influence of *Leucaena* on sorghum and sunflower using topsoil collected from the field either mulched with dry leaves or irrigated with aqueous leaf extract. Seed germination, root length, and dry matter production were reduced. Several other workers have also reported allelopathic effect of aqueous extracts of leaves, litter, soil, leaf leachate, seed exudate, dry leaf mulch, topsoil, and its allelochemicals. *Abelmoschus esculentus*, *Acacia confusa*, *A. nilotica*, *Ageratum conyzoides*, *Alnus formosana*, *Bidens pilosa*, *Brassica chinensis*, *B. juncea*, *Cajanus cajan*, *Casuarina equisetifolia*, *C. glauca*, *Cicer arietinum*, *Helianthus annuus*, *Lactuca sativa*, *Liquidambar formosana*, *Mimosa pudica*, *Miscanthus floridulus*, *Phaseolus vulgaris*, *Pinus taiwanensis*, *Stachytarpheta jamaicensis*, *Sorghum bicolor*, and *Vigna radiata* are some of the common species that are negatively sensitive to allelochemicals of *Leucaena* (Kuo et al., 1983; Chou and Kuo, 1986, Rizvi and Rizvi, 1987; Kuo et al., 1989; Chaturvedi and Jha, 1992; Rizvi et al., 1990a,b, 1994; Narwal, 1996; Sinha, 1996).

There are reports on the allelopathic effects of various plants on nitrogen fixation (Rice, 1984). Therefore, Rizvi and his associates selected nitrogenase, the enzyme for nitrogen fixation as a test parameter to measure the allelopathic activity of *Leucaena* leaves. They grew *V. radiata* in soil having *Leucaena* leaves, and in soil collected from under the canopy of 5-year-old *Leucaena* plants. They found that nitrogenase (N-ase) activity of plants grown with *Leucaena* leaves (8 g/kg) was 34% more than in the control plants, but this increase was reduced by 29% when the plants were grown with higher amount of leaves (16 g/kg). The N-ase activity was found to be reduced further when plants were grown in *Leucaena*-canopy soil, causing an inhibition of 28% when compared with the control (Rizvi, 1996; Sinha 1996).

According to a report of the International Institute for tropical Agriculture (Anon., 1980), the yield of maize (*Zea mays*) and rice (*Oryza sativa*) was increased when grown in association with *Leucaena*. Rachie (1983) also found an increase in the yield of maize intercropped with *Leucaena*. Studies conducted by Jeyaraman (1991) and Salazar et al. (1993) further supported a positive effect of *Leucaena* green leaf mulch on several growth and yield contributing parameters of rice, resulting in a higher yield. *Cajanus cajan*, *Sesamum indicum*, *Ricinus communis*, and

Sorghum vulgare are some of the other plants that are positively affected by *Leucaena* (Singh, 1983). However, there are contradictory reports about its effect on maize. Karim and co-workers (1991) have reported an inhibition of growth and yield of maize grown in association with *Leucaena* hedges.

The allelopathic effects of *Leucaena* are attributed to the presence of a number of phenolic compounds and mimosine (Table 1). Various concentrations of mimosine have been found to be inhibitory when applied to different plants. Radicle growth of lettuce (*Lactuca sativa*), rice, radish (*Raphanus sativus*), and turnip (*Brassica rapa*) was inhibited by 10 to 20 ppm of mimosine (Kuo et al., 1983; Tawata and Hongo, 1987). Germination, radicle, and plumule length of *Abelmoschus esculentus*, *Brassica campestris*, *Phaseolus aureus*, *Raphanus sativus*, *Triticum aestivum*, and *Vigna mungo* have been found to be inhibited by 1 m*M* mimosine. *Phaseolus aureus* and *V. mungo* were affected the most and showed an 83 and 86% inhibition of radicle growth, respectively (Rizvi et al., 1990a,b).

Despite the reports on the allelopathic effects of mimosine, not much information on the mode of action is available. Rizvi and his associates have found that mimosine inhibited a large number of physiological and biochemical parameters in *V. mungo* and *P. aureus*. They found that mimosine inhibited seedling vigor, food mobilization efficiency, solubilization of starch, breakdown of proteins, and activity of amylase. The reduced amylase activity was at synthetic as well as catalytic level, and it was mediated by gibberellic acid. They further reported that mimosine altered the hormonal balance of the seedlings leading to an inhibition in their growth. When *V. mungo* plants were grown in the soil having different amounts of *Leucaena* leaves, nitrogenase activity of root nodules was inhibited (Rizvi et al., 1990a,b, 1994; Rizvi and Rizvi, 1998).

A report by Prasad and Subhashini (1994) also confirms that the inhibitory effects of mimosine on germination and seedling growth of rice is mediated through its effect on nitrate reductase, catalase, IAA-oxidase, peroxidase, and its isozymes. Further studies on the mode of action of allelochemicals produced by AF species would help in understanding the mechanism of tree-crop interaction in agroforestry system.

IV. AGROFORESTRY AND PEST CONTROL

Plants are known to synthesize allelochemicals that affect germination, growth, metabolism, development, distribution, behavior, and reproduction of other organisms (Inderjit et al., 1994; Rice, 1995; Narwal et al., 1997). The presence of these allelochemicals often imparts plant resistance to pathogens, insects, nematodes, and reduces infestation of weeds (Rice, 1984, 1995; Green and Hedin, 1986; Chou and Waller, 1989; Rizvi and Rizvi, 1992a; Copping, 1996).

Agroforestry systems provide an excellent opportunity to explore the pest controlling properties of AF species. Most of the AF species produce a good amount of leaf, litter and debris that are rich in allelochemical content. These allelochemicals in turn provide various kinds of pest controlling properties to AF species. Thus, their allelopathic materials can be used as mulch, and their leachates and purified compounds may be eco-friendly alternatives to synthetic pesticides.

A. Agroforestry in Weed Control

Trees can regulate the germination and growth and development of weeds, through allelopathy. Scopolin and Scopoletin isolated from *Celtis laevigata* are reported to suppress *Amaranthus palmeri* (Lodhi and Rice, 1971). Ethanolic extracts of seeds of *Annona squamosa*, *Carica papaya*, *Coffea arabica*, and *Tamarindus indica* were found to inhibit germination of *Amaranthus spinosus* by 13, 58, 100, and 36%, respectively (Rizvi et al., 1980 b). They isolated and identified an allelochemical as 1, 3, 7-trimethylxanthine (1,3,7-T) from the seeds of *C. arabica*. When tested for herbicidal potential, it completely inhibited the seed germination of *A. spinosus* at 1200 ppm. The compound also suppressed the germination of *Avena fatua* (40.1%), *Echinochloa colonum* (100%), and *E. crusgalli* (91.2%) at a concentration of 2000 ppm. Rizvi and his associates further studied the selective behavior of 1,3,7-T and its mode of action on *A. spinosus*. While completely inhibiting the weed, it did not affect the germination and growth of *Vigna mungo* in which the weed is a problem (Rizvi et al., 1980c, 1987; Rizvi and Rizvi, 1983, 1984). Allelochemi-cals like mimosine, 3,4-dihydroxy pyridine, and phenolics present in *Leucaena* have also been found to totally exclude weeds like *Ageratum conyzoides* and *Mimosa pudica* (Chou and Kuo, 1986; Chou, 1993).

Seed germination and seedling growth of *Amaranthus retroflexus, Avena sativa, Chenopodium album,* and *Cynodon dactylon* were found to be inhibited by aqueous extracts, decaying materials, and volatile compounds of senescent and nonsenescent leaves of *Citrus aurantium* (Al-Saadawi and Al-Rubeaa, 1985; Al-Saadawi et al., 1985). Dried mango (*Mangifera indica*) leaf powder @ 250 g/10 kg mixed with soil in pot culture completely inhibited the germination of *Cyperus rotundus* up to 21 days, and its application to seedling considerably inhibited (60%) the tillering (Mohanty et al., 1994). *Eucalyptus* spp., because of high allelopathic activity, are expected to control weeds (Kohli et al., 1998a). *Eucalyptus* leaf leachate and oil showed differential effects on the growth of two weeds. A 20% leaf leachate suppressed the biomass production of *Cynodon dactylon* by about 50%, whereas 1% oil caused a 68% reduction. Application of 1% oil significantly inhibited shoot and root length, leaf chlorophyll, and total biomass production of *Cyperus rotundus* (Babu et al., 1996). Aqueous extracts of its bark, leaves, and oil inhibited *Parthenium hysterophorus* (Kohli et al., 1998b). Based on the chemistry of cineole (a component of *Eucalyptus* oil), a commercially used bioherbicide — cinmethylene — has been developed (Duke, 1986). Ailanthone, another chemical (isolated from *Ailanthus alissisma*), has been reported to possess a post-emergence herbicidal property similar to glyphosate and paraquat (Heisey, 1996).

The herbicidal properties of AF species appear promising. Some of the examples of allelochemicals that have demonstrated weed-suppressing ability are given in Table 2.

B. Agroforestry in Pathogen Control

One strategy to exploit allelopathy is the use of allelochemicals for the control of pathogens (Rice, 1995). The plant allelochemicals can be used either in the purified form, in the form of crude plant extracts or as volatile extracts. However, very few tree-based allelochemicals have been exploited for this purpose. Neem (*Azadirachta indica*) is one tree, which possesses potential to kill pathogens (Ghwande, 1989; Schmutterer, 1995a). Its seed cake, seed and fruit extracts, seed kernel powder, and seed oil have been reported to control a wide spectrum of fungal pathogens (Gunasekaran et al., 1986; Jeyarajan et al., 1987; Srivastava et al., 1997). The biological activity of neem against pathogens is attributed to the presence of sulfurous compounds in its seed oil. Moreover, neem products also act as deterrents to pathogen-carrying insects, thereby decreasing the disease incidence (Saxena et al., 1985; Eppler, 1995). Besides neem, some other AF species have also been evaluated for their effect on pathogens. Some of the examples can be seen in Table 3.

C. Agroforestry in Nematode Control

Neem (*Azadirachta indica*) is a plant species that has been studied for the nematode control. Various parts of neem or their extracts have been found nematicidal against *Meloidogyne incognita*.

TABLE 2
Allelochemicals Isolated from Agroforestry Species with Weed-Suppressing Properties

Allelochemical	Chemical nature	Natural source	Ref.
Ailanthone	Quassinoid	*Ailanthus altissima*	Heisey, 1996
Caffeine	Alkaloid	*Coffea arabica*	Rizvi et al., 1980c
Cineole	Terpenoid	*Eucalyptus globulus*	Kohli et al., 1998a
Citronellal	Terpenoid	*Eucalyptus citriodora*	Kohli et al., 1998a
Mimosine	Non-protein amino acid	*Leucaena leucocephala*	Rizvi, 1998
Azadirachtin	Sesquiterpene lactone	*Azadirachta indica*	Koul et al., 1990

TABLE 3
Agroforestry Species with Potential to Control some Crop Pathogens

AF species	Plant part/chemicals	Pathogen	Reference
Acacia arabica	Roots, seeds, and bark extracts	*Pyricularia oryzae*	Prakash et al., 1989
Aegle marmelos	Leaves	*Sclerotonia sclerotirum*	Ram, 1989
Azadirachta indica	Leaf extract, oil, essential oils	*Phaeoisariopsis personata* *Mycobacterium tuberculosis* *Sclerotum rolfsii* *Staphylococcus aureus,* TOSWV	Ghwande, 1989 Singh and Dwivedi, 1990 Ganapathy and Narayansamy, 1990
	Neem cake	*Fusarium solani* *Ganoderma lucidium* *Macrophomina phaseolina* *Phytophthora capsici* *Rhizoctania solani*	Jeyarajan et al., 1987
	Aqueous bark extract, Nimbidin	TMV PVX	Murty, 1982 Verma, 1974
	Commercial products	TMV, ZYMV, vectors	Eppler, 1995
	Seed kernel extract	*Xanthomonas campestris*	Eswaramurthy et al., 1993
Callistemon lanceolatus	Essential oil	*Pythiun aphanidermatum*	Kishore and Dwivedi, 1991
Citrus limone	Fresh leaves	*Cockliobolus miyabeanus* *Pyricularia oryzae* *Rhizoctonia solani*	Tewari and Nayak, 1991
	Essential oil	*Pythium aphanidermatum*	Kishore and Dwivedi, 1991
Coffea arabica	1,3,7-Trimethylxanthine	*Drechslera maydis*	Rizvi et al., 1980a
Eucalyptus spp.	Volatile and nonvolatile fractions	*Sclerotum rolfsii*	Singh and Dwivedi, 1990
E. rostrata	Essential oil, leaf powder	*Sclerotum capivorum*	Salama et al., 1988
Emblica officinalis	Extracts of different parts	*Pyricularia oryzae*	Prakash et al., 1989
Juniperus communis	Essential oil	*Pythiun aphanidermatum*	Kishore and Dwivedi, 1991
Lawsonia inermis	Leaf extract	*Phaeoisariopsis personata*	Ghwande, 1989
Lonchocarpus castilloi	Flavonoids of hardwood	*Lenzites trabea*	Gomez-Garibay et al., 1990
Pinus spp.	Essential oils	*Pythiun aphanidermatum*	Kishore and Dwivedi, 1991
P. taeda	Soil amended with bark	*Pythium aphanidermatum* *Fusarium* sp. *Rhizoctonia* sp.	Huang and Kuhlman, 1991
Pongamia pinnata	Leaf extract	*Phaeoisariopsis personata*	Ghwande, 1989
Saraca indica	Leaf extract	*Pythium debaryanum* *Fusarium oxysporum*	Kumar and Tripathi, 1991
Terminalia arjuna	Extracts of different parts	*Pyricularia oryzae*	Prakash et al.,1989
T. belerica	Extracts of different parts	*Pyricularia oryzae*	Prakash et al.,1989
Vitex negundo	Extracts of different parts	*Pyricularia oryzae*	Prakash et al.,1989

Leaves (Singh and Sitaramaiah, 1967, 1969; Vijayalskshmi et al., 1979); flower, bark, and gum (Siddiqui and Alam, 1985); seeds (Mishra et al., 1989) and seed coat kernel/cake (Mojumder and Mishra, 1991a,b) are some of the most studied parts. Nematode populations and root galling have been inhibited by extracts of neem in *Abelmoschus esculentus*, *Lycopersicon esculentum*, and *Solanum tuberosum* (Singh and Sitaramaiah, 1967; Rossher and Zebitz, 1987); chickpea (*Cicer arietinum*) (Gupta and Ram, 1981); mungbean (*Vigna radiata*), pulses and vegetable crops (Mojumder, 1997). Reddy et al. (1997) listed more than 20 nematode species that are susceptible to neem or chinaberry (*Melia azadirach*) derivatives.

Castor (*Ricinus communis*) is another AF species known to have nematicidal activity. Its oil cake has been found to reduce galling on okra (*Abelmoschus esculentus*) roots caused by *Meloidogyne javanica* (Singh, 1969). In spinach (*Spinacea oleracea*), soil population of *M. incognita* was suppressed and root galling was reduced by the treatment of its oil cakes (Alam and Khan, 1974). Khan and his associates have found that the soil population of *M. incognita* in tomato fields was reduced when treated by castor oil cakes (Khan et al., 1969, 1973). A reduction in the number of *M. incognita* and *Meloidogyne* sp., root galling, and an increase in tomato yield when cultivated in the presence of castor cake have been reported by Hasan (1992). Some of the other tree species, which are reported to suppress nematodes, are *Acacia auriculiformis* (Sinhababu *et al*., 1992), *Coffea* sp. (Tronocon et al., 1986), and *L. leucocephala* (Jain and Hasan, 1985).

Apart from using plant parts or their extracts, purified allelochemicals could also be used for nematode control. However, only a few allelochemicals have been isolated and identified that are active against nematodes. Alkaloids like nimbidin and thionemone isolated from neem have been found toxic to a number of phytoparasitic nematodes (Khan et al., 1974a,b). Further studies are needed to demonstrate the benefits of agroforestry in nematode control.

D. Agroforestry and Insect Control

The insect repellent property of neem (*Azadirachta indica*) was first discovered in India in 1928, and the neem leaves were used in protecting stored rice from insect infestation. However, significant advancement in the insect controlling potential of neem started in the 1960s. H. Schmutterer rediscovered the properties of neem tree that control insects while working in Sudan during a locust invasion in 1959. The next 3 decades witnessed an unprecedented increase in research activities throughout the world.

Neem products, ranging from simple leaf and seed kernel powders, their extracts, oil, cake, active compounds, and several commercial products, have been tested against 450 to 500 species of insects. Schmutterer (1995a) has listed 413 species or subspecies that are susceptible to neem products. Some of the neem allelochemicals tested for their efficacy against various insect pests are azadirachtins, azadirones, nimo- and nimbocinolides, salannins, vilasinines, nimbenene and 6-deacetylnimbinene, margosinolides, meliantriol, alkanes, and several sulfur-containing compounds (Koul, 1992). Neem products or their formulations have been found to be effective against insect pests in corn (Hellpap, 1995); oil crops (Zebitz, 1995a); vegetables and grain legumes (Ostermann and Dreyer, 1995); fruit trees, root, and tuber crops (Zebitz, 1995b,c); forest, ornamental trees, and shrubs (Schmutterer, 1995b); blood sucking and other parasites of man and domestic animals (Schmutterer, 1995c); and pests of stored products (Saxena, 1995). Readers interested in details may refer to Schmutterer and Ascher (1984, 1987), Schmutterer (1995a), and Narwal et al., (1997).

Besides neem, only a few plant species (known for agroforestry uses) have been evaluated for their insect-controlling property. Rizvi and his associates isolated a compound 1,3,7-trimethylxanthine from seeds of coffee (*Coffea arabica*) and tested it as a chemosterilent against stored grain pest-*Callosobruchus chinensis*. They found that at 1.5% concentration the compound significantly inhibited the oviposition (Rizvi et al., 1980d). Oil extracted from seeds of *Annona squamosa* showed a significant reduction in survival of rice leafhopper (*Nephotettix virescens*) and thereby transmission of rice tungro virus (Prakash et al., 1989). They further reported that leaves of *Vitex negundo* are effective against *Rhizopertha dominica*, *Sitotroga cerealella*, and *Tribolium castanem.* Insects like *Achaea janta*, *Bruchus chinensis, Diacrisia obliqua, Euproctis fraterna, Sitotroga cerealella*, *Spodoptera litura*, and *Scirpophaga* sp. were also inhibited by *V. negundo.* Shin-Foon (1987) reported that seed oil of *Melia azadirach* is effective against citrus red mite *(Panonychus citri*) and orange spiny white fly (*Aleurocanthus spiniferus*). He further reported that toosendanin, a triterpenoid isolated from the bark of *M. toosendan*, possesses antifeedant and growth-disturbing properties against cabbage worm — *Pieris rapae*. When methanolic extract, stem, and bark of *Grewia microcos* were tested for their anti-insect properties against *Aedes* *aegytii, Plutella xylostella*, and *Callosobruchus chinensis*, the LC-50 of methanolic extract against second-instar mosquito larvae was found to be 47.5 ppm (Permaratne et al., 1996).

Indiscriminate use of synthetic pesticides is a serious global problem. Several of them have been found to be hazardous due to their long persistence, health-related problems, environmental pollution, and non-target toxicity (Rizvi et al., 1998, Rizvi and Rizvi, 1992 b). The organophosphorus compounds are especially dangerous because they are known to attack the nervous system (Vighi and Funari, 1995; Van Emden and Peakall, 1996). By contrast, the botanicals (allelochemicals), with some exceptions, are considered to be less toxic to non-target species and environmentally safer owing to their biodegradable nature (Copping, 1996). Thus, plants may prove a neverending reservoir of eco-friendly allelochemicals because they are likely to be recycled through nature. Agroforestry species remain a component of agroecosystem for comparatively longer period; therefore, their possible ability to control pests could be of great value.

V. APPROACHES FOR FUTURE RESEARCH

A. Qualitative Yield of Agroforestry Systems

Agroforestry, besides being an important tool for developing sustainable land use, is also considered a system to increase food production, especially for rural people. In less-developed and developing countries, the latter goal of agroforestry becomes more crucial because the majority of the rural population depends on food from their small land holdings. Thus, any recommended agro-forestry system should ensure production of sufficient food (especially the grains obtained from the crop component of agroforestry), without compromising the nutritional value of the product. Unfortunately, while evaluating the grain yield of agroforestry systems, a gross increase in the quantity of grains (if any) invariably has been considered a measure of the increase in food production. However, studies conducted by Rizvi et al. (1990b) and Sinha (1996) have demonstrated that allelochemicals released from AF species also affect the quality of food grains. When *Vigna radiata* was grown in monoculture and in alley cropping with *Leucaena,* iron content of grains obtained from the latter was reduced by 72%. Thus, even if the grain yield potential is high, the possibility of producing grains with low nutritive value cannot be ruled out. On the contrary, when plants of *V. radiata* were grown in the presence of leaves of *Moringa oleifera*, the level of zinc and iron content in grains was increased by 28 and 45%, respectively (Rizvi and Rizvi, unpublished data). Thus, it is extremely important to conduct similar studies with other AF species to ensure the supply of food with at least normal nutritive value or if possible, with an improved quality. Agroforestry systems designed on the basis of the above considerations could improve the quality of life of the poor and malnourished.

B. Soil Quality and Replant Problem with Agroforestry Species

In agroecosystems, nurseries, and agroforestry systems where the same crops are grown year after year, the *Replant Syndrome* often appears, which pertains to the injurious effect on the succeeding crops. It often makes the land unfit for further use. To rejuvenate such soils and reestablish the crops in these is difficult. Data suggest that in most of these problems allelopathy plays an important role either directly, or through mediation of microorganisms, nematodes, and other soil biota. The replant problem is at least partly due to the presence of allelochemicals released in the soil from the roots of the intact plants, fallen litter, or the post-harvest residues left in the soil. In some cases, the allelochemicals responsible for the same have been identified, such as amygdalin in peach (*Prunus persica*) and phlorizin and phloretin in apple (*Malus baccata*) (Rice, 1984).

The problem is prevalent especially in the orchards, nurseries, and agricultural fields where the same cropping pattern is repeated year after year. As early as in the beginning of this century, Schreiner and Reed (1908) reported the replant problem of crops and attributed this to deterioration of soil caused by the toxins released from the previous crops. Their study concluded that the removal of the toxins from the soil overcomes this problem. Although continuous cropping of the same species is successful in many parts of the world, replant problem has been documented from some of the countries. A number of crop plants like coffee (Friedman and Waller, 1983), alfalfa (*Medicago sativa*) (Miller, 1983), wheat (Thorne et al., 1990), rye (*Secale cereale*) (Wojcik-Wojtkowiak, 1990), maize (Yakle and Cruse, 1983), and rice (Chou and Lin, 1976) in addition to orchard crops are known to suffer with this problem. Recently, Duhan et al. (1994) found that soil of *Acacia nilotica* rhizosphere inhibits the nitrogenase (N-ase) activity in *Rhizobium* sp. Rizvi (1996) has also found a 28% inhibition in the N-ase activity of root nodules of *Vigna radiata* plants when grown in *Leucaena*-canopy soil. These findings indicate toward the possibility of soil health problem in agroforestry systems.

C. Selective Behavior of Tree Allelochemicals

It has been reported that AF species behave differentially with companion crops (Anon., 1991). Kuo and his associates reported that only a few understorey species grow under the *Leucaena* canopy, but a substantial number of its own seedlings were able to grow. Experimental data on light, soil moisture, and nutrients, etc. revealed that competition for these factors was not the major cause for the phenomenon of exclusion of understorey vegetation (Kuo et al., 1983; Chou and Kuo, 1986; Chou, 1993). Rizvi and his associates evaluated the effect of *Leucaena* leaf leachate on *Abelmoschus esculentus*, *Brassica juncea*, *Cajanus cajan*, *Cicer arietinum*, *Oryza sativa*, *Phaseolus vulgaris*, *Vigna radiata*, and *Zea mays*. Except for *O. sativa*, all other crops were significantly inhibited by *Leucaena* leachate (Rizvi, 1996; Sinha, 1996). Similar effects were observed with pure mimosine (Rizvi and Rizvi, 1987; Rizvi et al., 1990a,b). *Vitex negundo*, a dominant component of coastal vegetation, is widely distributed in the southern parts of Taiwan. Chou and Yao (1983) found that the biomass and density of its understorey vegetation are relatively lower than in adjacent pastures. Field results showed that the natural leachates of *V. negundo* significantly retarded the growth of *Digitaria decumbens* but stimulated the growth of *Andropogon nodosus* when compared with the rainfall control. The growth of *D. decumbens*, grown in pots under green house conditions, was significantly retarded by watering with a 1% aqueous extract of *V. negundo*, but the growth of *A. nodosus* and *Mimosa pudica* was inhibited. Kil (1992) reported a selective pattern in understorey vegetation of pine stands when compared with the adjoining area. Species such as *Aster tataricus*, *Cymbopogon tortilis*, *Themeda triandra*, and *Plantago asiatica* were found to grow well inside the pine forest, where species such as *Boehmeria plantanifolia*, *Cassia tora*, *Chenopodium album*, and *Digitaria sanguinalis* were growing only outside the forest. This selectivity was attributed to the presence of a number of phenolic allelochemicals in pine leaves and canopy soil.

The yield of wheat, green gram (*Vigna radiata*), and turmeric (*Curcuma longa*) was reduced when grown in alley cropping with *Leucaena*, but the yield of maize and rice was increased (Anon., 1991). Research conducted at the International Institute for Tropical Agriculture (Anon., 1980), and by Rachie (1983) further supported a positive effect of *Leucaena* on the yield of maize and rice. Studies conducted by Jeyaraman (1991) and Salazar et al. (1993) also demonstrate a positive effect of *Leucaena* green leaves on several growth and yield parameters in rice. They found that the rice plant was not only tolerant to negative allelopathic effects, but it gave a higher yield with *Leucaena* mulch. Such observations on the selective allelopathic behavior of AF species for companion crops could be of practical value in designing agroforestry systems.

Selective action of a chemical can be attributed to several factors viz. some detoxifying mechanism in the receptor plant; concentration of allelochemical in the producer plant, soil, and site of action at a particular time; activity of microbes and environmental conditions, etc. However, research is lacking in this area. Smith and Fowden (1966) have demonstrated that *Leucaena* seedlings detoxify mimosine into 3,4-dihydroxypyridine, which is further broken down into nontoxic metabolites. Rizvi and his associates found variation in allelochemical concentration in *Leucaena* leaves over the year. While studying the effect of leachates (prepared from the leaves collected every month) on *V. mungo*, they found the radicle growth inhibited by 10 to 62%. Thus, the adverse effect on the companion crops grown during the high allelochemical concentration period is obvious (Rizvi et al., 1994; Sinha, 1996). Similar studies with other AF species are needed to make suitable selections of companion crops. Further, such studies may also prove to be useful from the viewpoint of animal nutrition.

D. Allelochemicals: Role in Animal and Human Nutrition

One of the major goals of agroforestry is to provide fodder for farm animals. This is even more important for the farmers of developing countries. The populations of most of these countries have only small land holdings, and they almost completely depend on farm for their food, fodder, and other needs. In these circumstances farmers have a high expectation from their agroforestry endeavors. This includes a regular supply of suitable, nutritious, and less-expensive fodder. Being completely dependent on their farm animals for agricultural and economic purposes, the health of livestock is always a concern. Therefore, the agroforesters must guarantee that the fodder available through agroforestry is not only cheaper and nutritious, but safer as well. Unfortunately, the roles of allelochemicals in this regard have almost been totally ignored. Rizvi and Rizvi (1992b) have emphasized that it is desirable to evaluate the tree component of agroforestry systems from this viewpoint. Only limited information is available with the exception of allelochemicals such as mimosine and canavanine produced by *Leucaena leucocephala* and *Gliricidia sepium*, respectively.

The presence of a high amount of crude protein, potassium, calcium, phosphorus, carotenes, vitamin K, and riboflavin in *Leucaena* leaves make it desirable as an animal feed. However, researchers have found that *Leucaena* can be toxic to animals. Most conspicuous of these adverse effects are the loss of hair in nonruminant animals and the reduction of egg production in poultry. Cattle fed excessively on *Leucaena* meal suffer from hair loss, poor growth, and excessive salivation (Ritchie, 1974). Mimosine can also cause the formation of goiter, deterioration in the quality of wool, retarded growth, fertility problems, and general adverse effects on health, which may eventually lead to mortality. Mimosine is known to inhibit a number of biochemical reactions. It acts as a tyrosine antagonist and competes with tyrosine to inhibit the activity of tyrosinase, reduces synthesis of high-tyrosine proteins and DNA, and leads to reduction of blood thyroxin (Ries et al., 1975; Hegarthi *et al*., 1976; ter-Meulen and El-Harith, 1985; Bray, 1986). It has also been reported to inhibit tyrosine decarboxylase, aspartate glutamate transaminase, and synthesis of RNA and proteins (Bell, 1972; Kuo et al., 1983). Earlier, the toxicity of *Leucaena* was ascribed to its ability to accumulate selenium from soil (Arnold, 1944). However, Yoshida (1994) working with rats has shown that the loss of hair and other toxic symptoms that developed when rats were fed on *Leucaena* meal were not due to selenium accumulation but rather to mimosine.

The expression of mimosine toxicity depends on the rumen microbial ecology, and the level of toxicity is related to the extent and rate of bacterial breakdown of mimosine. During degradation of mimosine, two isomers viz. 3-hydroxy-4 (1H)-pyridone (3,4-DHP) and 2,3-DHP are produced. Some of the rumen bacteria are capable of detoxifying both forms of DHP, but the possibility exists that considerable quantities of mimosine and 3,4-DHP may escape such degradation (Bray, 1986; D'Mello, 1994). The nature of bacteria in ruminants varies in different geographical regions. In those regions where *Leucaena* is indigenous (Central America) or is naturalized (Hawaii and Indonesia), ruminants possess the bacteria required for breakdown of mimosine and its degradation products. This leads to the absence of *Leucaena* toxicity. However, in other regions like Australia, Kenya, and the U.S.A., ruminants lack the bacteria that are required to detoxify mimosine and its isomers. Therefore, in these regions it is common to observe mimosine toxicity in ruminants fed on

Leucaena meal for a long period. If ruminants are inoculated with DHP-degrading bacteria, the problem of mimosine toxicity can be solved. Such uses have been demonstrated successfully in Australia (Brewbaker, 1989). Another AF species, *G. sepium*, is known to contain a highly toxic allelochemical — canavanine. Besides being allelopathic (Bass et al., 1995), it is known to enhance arginine catabolism; reduce the synthesis of polyamine, creatine, and DNA; compete with lysine and arginine for transport and induce synthesis of aberrant proteins (D'Mello, 1994).

Thus, the presence of harmful allelochemicals in fodder may totally jeopardize one of the important goals of agroforestry. The reports that mimosine has also caused toxic effects in humans are even more disturbing (Brewbaker, 1989). Toxic allelochemicals or their degradation products may enter the human body in several ways: (1) through direct consumption of allelochemical containing material, (2) as a residue in crop plants grown in association with allelopathic AF species, and (3) through consumption of products obtained from animals fed on a high allelochemical (toxic) diet. Therefore, it is essential for nutritionists to study the possible harmful or beneficial effects of tree-allelochemicals. Such studies are more crucial when an alien species is being introduced as a component of the agroforestry system into a new geographical zone.

VI. CONCLUSION

In recent years, great concern has been expressed regarding degrading environment, depleting biodiversity, and deteriorating natural resource base on a global level. These problems are primarily because of an increase in the population, misuse or overuse of natural resources, deployment of a huge amount of agrochemicals, cultivation of aggressive or more competitive varieties, and the introduction of exotic tree species. Agroforestry is now considered an effective tool to combat these problems and develop a sustainable agroecosystem. However, the introduction of the concept of allelopathic compatibility between various components of the agroforestry system is further expected to increase its utility and productivity besides conservation of the environment, biodiversity, and natural resource base.

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