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Degraded land rehabilitation through agroforestry in India: Achievements, current understanding, and future prospectives

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Land degradation is one of the most important factors responsible for the alarming situation of food security, human health, and socioeconomic development in the country. Currently, 120.7 M ha of land in the country is affected by land degradation, out of which 85.7 M ha of land is affected by soil erosion caused by water and wind. Moreover, physical, chemical, and biological degradation are the major forms of land degradation in the country. Deforestation or tree cover loss (2.07 M ha) from 2001 to 2021, intensive rainfall (>7.5 mm ha^{-1}), uncontrolled grazing (5.65 M ha), indiscriminate use of fertilizers (32 MT $year^{-1}$), and shifting cultivation (7.6 M ha) are other major factors that further aggravate the process of land degradation. In order to alleviate the problem of land degradation, numerous agroforestry technologies have been developed after years of research in different agroclimatic zones of the country. The major agroforestry systems observed in the country are agri-horticulture, silvipasture, and agri-silviculture. This review indicates the potential of agroforestry in enhancing carbon sequestration (1.80 Mg C ha^{-1} $year^{-1}$ in the Western Himalayan region to 3.50 Mg C ha^{-1} $year^{-1}$ in the island regions) and reduced soil loss and runoff by 94% and 78%, respectively, in Northeast India. This can be concluded that the adoption of the agroforestry system is imperative for the rehabilitation of degraded lands and also found to have enough potential to address the issues of food, environmental, and livelihood security. This review's findings will benefit researchers, land managers, and decision-makers in understanding the role of agroforestry in combating land degradation to enhance ecosystem service in India and planning suitable policies for eradicating the problem effectively.

KEYWORDS

acidic soils, carbon sequestration, mined area, ravine lands, soil erosion

Introduction

Land resources are the basis for human livelihood and societal development (Xie et al., 2020). Since the 20th century, land degradation has escalated and aggravated due to ecological degradation, increased food demand of a burgeoning population, rapid urbanization, industrialization, and indiscriminate use of land resources (Hammad and Tumeizi, 2012). Approximately 60% of the world's land area is regarded as degraded, which is considered one of the most important challenges to bringing them to sustainable use (Pimentel, 2006). It has been reported that accelerated land degradation is a major threat to soil, and ~24 billion tonnes (BT) of fertile soil is lost annually only through water erosion, and 75 BT of soil is eroded annually from arable lands globally, which resulted in the estimated financial loss of US $400 billion per year (GSP. Global Soil Partnership, 2017). In India, ~120.7 M ha of land suffers from various forms of degradation (NAAS, 2010). The primary process of land degradation is soil erosion (due to water and wind erosion), contributing ~71% of (85.7 M ha) degraded land in the country (Table 1). Water-induced soil erosion alone contributes ~60.7% (73.3 M ha), while wind erosion contributes 10.3% (12.4 M ha). The other processes include the problem of chemical (salinity, alkalinity, and acidity) and physical degradation (water logging and mining) also contribute significantly to the degradation of land resources. Deforestation or tree cover loss (2.07 M ha) from 2001 to 2021 (Global Forest Watch, 2022), intensive rainfall (>7.5 mm ha^{-1}), uncontrolled grazing in 5.65 M ha (Down To Earth, 2019), indiscriminate use (32 MT year^{-1}) of fertilizers (Fertilizer Association of India, 2021), and shifting cultivation in 7.6 M ha (Bhat et al., 2022) are other major factors that further aggravate the process of land degradation. According to SAC (2021), at present, 97.8 M ha (29.7%) of the area is degraded in the country. The states of Rajasthan, Maharashtra, Gujarat, Karnataka, Ladakh Union Territory, Jharkhand, Odisha, Madhya Pradesh, and Telangana have the highest area under such lands (23.7% of TGA), contributing about two-thirds of the total degraded area of the country.

Degraded lands are poor in organic matter and soil nutrients, which consequently do not support any kind of vegetation. In the absence of any management or conservation measures, these become irreversible and unproductive resulting in serious ecological and socioeconomic consequences. Rehabilitation of degraded lands is, therefore, one of the most viable options for improving land productivity. These degraded lands can be ameliorated by practicing agronomical, mechanical, and biological measures (Chaturvedi et al., 2018; Jinger and Kakade, 2019; Kumar et al., 2020). Biological measures which involve the growing of trees, shrubs, and crops/herbs are simple, cost-effective, and can help relieve the pressure on traditional cultivated lands and forests. Among different biological measures, agroforestry is considered ideal in terms of enhancing productivity and providing ecological and economic security. Furthermore, the agroforestry system also provides numerous ecosystem services (provisioning, regulating, supporting, and cultural), which directly or indirectly help in land restoration (Paramesh et al., 2019; Jinger et al., 2022b). India in COP 27 emphasized joining the LiFE movement—Lifestyle for Environment, a pro-people and pro-planet effort that seeks to shift the world from mindless and wasteful consumption to mindful and deliberate utilization of natural resources. Furthermore, India aimed to continue its battle against all global environmental challenges in the appeal to defend humanity's planetary home. India is dedicated to both domestic action and multilateral collaboration on climate change. However, global warming also issues a warning that success depends on equity and global cooperation, where the privileged must take the lead. To achieve a pollution-free environment, the adoption of climate-resilient practices is imperative. Agroforestry is one such potential eco-friendly system having huge scope to restore degraded land, fix atmospheric carbon, and also to enhance soil quality by reducing soil erosion.

TABLE 1 Harmonized area statistics of degraded land/wastelands of India (M ha).

Degradation type	Arable land (M ha)	Open forest (<40% canopy) (M ha)	Data source
Water erosion (>10 Mg ha^{-1} year^{-1})	73.27	9.30	Soil Loss Map of India-IISWC, Dehradun
Wind erosion (Aeolian)	12.40	–	Wind Erosion Map of India-CAZRI, Jodhpur
Sub total	85.67	9.30	
Chemical degradation			
Exclusively salt-affected soils	5.44	–	Salt-affected Soils of India, CSSRI, Karnal; NBSS&LUP, Nagpur; NRSA, Hyderabad and others
Salt-affected and water-eroded soils	1.20	0.10	
Exclusively acidic soil (pH < 5.5)	5.09	–	Acid Soils of India, CSSRI, Karnal; NBSS&LUP, Nagpur
Acidic (pH < 5.5) and water-eroded soil	5.72	7.13	
Sub total	17.45	7.23	Wasteland Map of India-NRSA, Hyderabad
Physical degradation			
Mining and industrial waste	0.19		
Waterlogging (permanent surface inundation)	0.88		
Sub total	1.07		
Total	104.19	16.53	
Grand total (Arable land open forest)	120.72		

With this background, we hypothesized that agroforestry is beneficial in the rehabilitation of degraded land and enhances the ecosystem services to improve the livelihood security of farm families for achieving sustainability. Considering the importance of the agroforestry system in carbon sequestration, biomass production, food production, industrial value, economics, and employment generation to the farm family, an attempt has been made to collect the published research outputs and perform a detailed review of the same. The objective of the study was to know the importance of agroforestry in improving carbon sequestration, biomass production, food production, economics, and soil fertility enhancement. The review is extended to collect information on degraded lands in India and its causes.

Furthermore, this chapter deals with agroforestry solutions for different kinds of degraded lands in India.

Literature search and data collection

We systematically searched for scientific literature using the following search terms in Google Scholar: "Agroforestry system AND Carbon sequestration AND Erosion control Food Production AND Land rehabilitation," of which the first 102 results were selected. Studies were selected if they included the agroforestry system and any of the keywords searched. We collected further records from the reference lists of review articles and research articles meeting the initial eligibility criteria. Targeted searches of governmental and independent agricultural research organizations were also performed in countries where medium to large-scale, commercially oriented agroforestry systems are known to occur.

- The study scope was extended to all the agroforestry systems such as agro-pastoral systems, agro-silvo-pastoral systems, agri-horti, silvipasture, and silvi-horti;
- Studies involving different land holding sizes were also considered;
- Both on-farm (farmer's field) and on-station (research station) trails were considered; and
- The study was original research, dataset, or dissertation, i.e., not a review, book chapter, or conference proceeding also considered.

Land degradation mechanism

Land degradation refers to the temporary or permanent decline in the biological productivity of land due to anthropogenic activities (United Nations Environment Programme, 1993; Xie et al., 2020). Land degradation also includes wind erosion and water erosion, resulting in the loss of soil material and long-term loss of natural vegetation (Warren, 2002). As a result, disasters such as floods and droughts are exacerbated, which seriously threatens the survival and development of humankind (Guo et al., 2018). Land degradation is the systematic decline in the quality of the land resulting from a mismatch between land use and land quality. It is the consequence of different natural processes, but it is accelerated by human activities. The result in declining functions (Chalise et al., 2019). The land undergoing degradation normally passes through three phases, *viz.* (1) Natural degradation is generally slow because a steady state develops between soil formation and soil degradation. Natural degradation represents inherent land quality, (2) induced degradation results from inappropriate land-use management. Soils decline in quality, but productivity can be maintained by applying artificial nutrients and by appropriate soil management. Induced degradation happens more quickly than natural degradation, and (3) desertification occurs when the degree of degradation is such that the resilience of the land is impaired. In unmanaged systems, desertification is indicated by changes in the quality and quantity of biomass and biota (Singh D. V. et al., 2017; Singh C. et al., 2017).

Types of land degradation

Mechanisms that initiate land degradation include physical, chemical, and biological processes. Important among physical processes is a decline in soil structure, leading to crusting, compaction, erosion, desertification, anaerobism, environmental pollution, and the unsustainable use of natural resources. Significant chemical processes include acidification, leaching, salinization, decrease in cation retention capacity, and fertility depletion. Biological processes include a reduction in total and biomass carbon and a decline in land biodiversity. The latter comprises important concerns related to the eutrophication of surface water, contamination of groundwater, and emissions of trace gases (CO_2, CH_4, N_2O, and NO_x) from terrestrial/aquatic ecosystems to the atmosphere. Soil structure is an important property that affects all three degradative processes (Lal and Steward, 1990) (Figure 1).

Factor affecting land degradation

The sustainability of natural resources is under serious threat due to indiscriminate cutting of trees, conversion of forest land into agriculture, shifting cultivation, exploitation of fragile and marginal lands, faulty management practices, and reduction in the frequency of fallowing and excessive use of chemicals (Sharda and Juyal, 2016). The problem is further compounded by over-exploitation of sweet ground water aquifers, ingress of sea water in the coastal ecosystem, floods, and droughts in different parts of the country (Table 2).

Agroforestry

Woody perennials (trees, shrubs, palms, bamboo, etc.) are intentionally used on the same land management units as annual crops and/or animals in some kind of spatial arrangement or temporal sequence, and these systems and technologies are together referred to as agroforestry. The various components of agroforestry systems must interact both ecologically and economically (Lundgren and Raintree, 1982). Agroforestry has a great deal of promise to supply the demand for fuel, fodder, timber, medicine, and other non-woody forest products while boosting green cover, easing the strain on forests, and reducing greenhouse gas emissions. Agroforestry provides a practical way to prevent hazards brought on by weather anomalies, manage soil erosion, and guarantee long-term sustainable output. Central Agroforestry

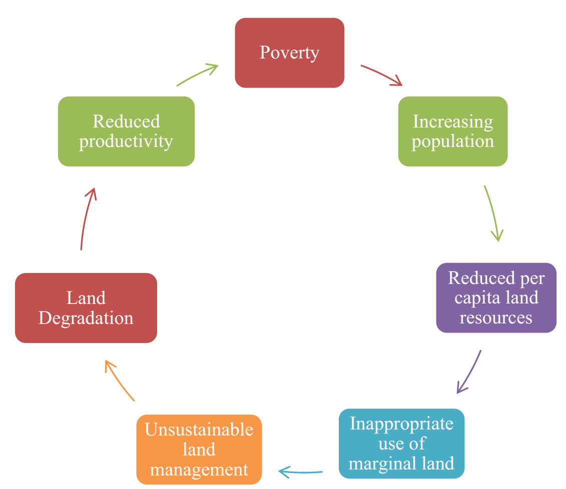

FIGURE 1
The cycle of processes leading to and perpetuating land degradation.

TABLE 2 Major factors affecting land degradation.

Particular	Activities	References
Unsustainable agricultural practices	• Extensive and frequent cropping on agricultural lands	Bhattacharyya et al. (2015)
	• Excessive use of fertilizers	Chandini et al. (2019)
	• Shifting cultivation without allowing an adequate period of recovery	Markose and Jayappa (2016)
	• Excessive tillage	Hobbs et al. (2008)
	• Residue burning	National Academy of Agricultural Sciences (2012)
Unsustainable water management	• Poor and inefficient irrigation practices	Barman et al. (2013)
	• Over-abstraction of ground water	Farid et al. (2019)
Conversion of land for other uses	• Prime forest into agriculture land	Wairiu (2017)
	• Encroachment of cities and towns in to agricultural lands	Sahu and Dash (2011)
Deforestation	• Forest land clearance for agriculture including shifting cultivation	Hossain (2011)
	• Over grazing	Nicu (2018)
Others	• Industrial, mining, and other activities without satisfactory measures for the prevention of land degradation and land rehabilitation	Chaturvedi et al. (2014)
	• Demographic pressure–human and livestock	Mythili and Goedecke (2016)
	• Frequent drought/failure of monsoon and their link with global climate phenomena	The Energy and Resources Institute (2016)

Research Institute, Jhansi, recently reported a 26.3 m ha area under agroforestry in India (Arunachalam et al., 2021).

Agroforestry practices in India

Indian traditional agroforestry systems range from seemingly straightforward forms of shifting cultivation to intricate home gardens, from systems involving sparse stands of trees on farmlands to high-density complex multi-story homesteads of humid lowlands, and from systems in which trees primarily serve as a "service" to those in which they are the primary source of commercial good. The majority of them are anecdotal, but some of them have received enough research in recent years (GOI, 2001; Pathak et al., 2006). The foundation of the All India Coordinated Research Project on Agroforestry (AICRPAF) by the Indian Council of Agricultural Research (ICAR) at 20 centers in 1983 and the subsequent construction of the National Research Centre for Agroforestry at Jhansi in 1988 marked the beginning of systematic agroforestry research in the nation. There are currently 37 agroforestry centers operating throughout the nation. Agroforestry research was also started by the Indian Council of Forestry Research and Education (ICFRE) in various regions of the nation. Agroforestry research was also started by numerous business corporations limited companies, including ITC (Indian Tobacco Company Limited), WIMCO (Western India Match Company), West Coast Paper Mills Ltd., Hindustan Paper Mills Ltd., and others, with a focus on the production of improved planting material of the fast-growing species to meet their demand for raw materials (Dhyani et al., 2015). A diagnosis and design exercise for current agroforestry methods in India has been carried out through ICAR centers. The survey revealed agri-silviculture as the most prominent agroforestry system in seven agroclimatic regions, followed by agri-horticulture in six agroclimatic regions, and agri-hortisilviculture and silvi-pastoral systems in two agroclimatic regions.

Types of agroforestry system: Based on structure, agroforestry can be grouped into agri-silviculture, agri-horticulture, agri-silvi-horticulture, silvi-pasture, horti-pasture, and agri-silvi-pasture system.

TABLE 3 Most prevalent agroforestry systems in agro-climatic zones of India.

Agro-climatic zone	Agroforestry system	Components
Western Himalayan Region	Agri-horticulture	*Prunus armeniaca/Prunus persica* + *Ocimum sanctum*, *Malus pumila* + millets/wheat
	Silvipasture	*Morus alba* + *setaria anceps*
Eastern Himalayan Region	Silvipasture	*Morus alba* + *Pennisetum purpureum*/setaria *anceps*
	Agri-silviculture	*Anthocephalus cadamba* + paddy
	Agri-horticulture	*Alnus nepalensis* + coffee
Lower Gangetic Plains	Agri-silviculture	*Eucalyptus tereticornis* + paddy-wheat
	Agri-horticulture	Mango/banana/litchi + wheat, paddy, maize
	Silvipasture	*Morus alba* + *Dicanthium annulatum Albizia lebbeck* + *Pennisetum purpureum*
Middle Gangetic Plains	Agri-silviculture	*Populus deltoides/Eucalyptus* + rice-wheat, *Tectona grandis* + sorghum/groundnut
	Agri-horticulture	Mango/citrus + rice-wheat
	Silvipasture	*Albizia lebbeck* + *Dicanthium annulatum*
Trans-Gangetic Plains	Agri-silviculture	*Azadirachta indica* + blackgram-wheat/mustard, *Populus deltoides* + wheat/potato/turmeric
	Agri-horticulture	*Emblica officinalis* + blackgram/greengram
	Silvipasture	*Bauhinia variegata* + *Cenchrus ciliaris*
Upper Gangetic Plains	Agri-silviculture	*Populus deltoides/Eucalyptus* + rice-wheat, *Dalbergia sissoo* + mustard
	Silvipasture	*Bauhinia variegata* + *Chrysopogon fulvus*
Eastern Plateau and Hills Region	Agri-silviculture	*Acacia nilotica/Gmelina arborea* + paddy, *Albizia procera* + wheat
	Silvipasture	*Leucaena leucocephala* + *Dicanthium/Pennisetum/Chrysopogon*
Central Plateau and Hills Region	Agri-silviculture	*Acacia nilotica/Leucaena leucocephala/Azadirachta indica/Albizia lebbeck* + *soybean/blackgram-wheat/mustard*
	Agri-horticulture	*Emblica officinalis* + blackgram/greengram, *Psidium guajava* + chickpea/groundnut
Western Plateau and Hills Region	Agri-horti-silviculture	*Tectona grandis* + paddy, *Manilkara zapota* + maize
	Agri-silviculture	*Ailanthus excelsa* + cowpea-mustard
	Silvipasture	*Acacia mangium* + *Cenchrus ciliaris*
Southern Plateau and Hills Region	Agri-silviculture	*Eucalyptus tereticornis* + cotton/chilli
	Agri-horticulture	*Tamarindus indica* + chilli
	Silvipasture	*Leucaena leucocephala* + *Stylosanthes hamata*
East Coast plains and Hills region	Agri-silviculture	*Ailanthus excelsa* + cowpea
	Silvipasture	*Artocarpus* + *Cenchrus ciliaris/Pennisetum purpureum/Chrysopogon fulvus*
	Horti-silviculture	*Acacia mangium* + pineapple
West Coast Plains and Ghats Region	Agri-silvi-horticulture	*Acacia auriculiformis* + *Artocarpus heterophyllus* + black pepper
	Silvipasture	*Hardwickia binata* + *Cenchrus ciliaris*
Gujarat Plains and Hills Regions	Agri-silviculture	*Azadirachta indica* + cowpea, *Ailanthus excelsa* + greengram
	Silvipasture	*Leucaena leucocephala* + *Cenchrus ciliaris*
	Silvo-aromatic	*Melia dubia* + lemon grass
Western Dry Region	Agri-silviculture	*Prosopis cineraria* + pearl millet
	Silvipasture	*Albizia lebbeck/Ailanthus excelsa* + *Cenchrus ciliaris/panicum antidotale*
The Island Regions	Agri-horticulture	*Cocos nucifera* + paddy
	Horti-pasture	*Cocos nucifera* + *calliandra calothyrsus*
	Silvipasture	*Bauhinia variegata* + *Cenchrus ciliaris, Erythrina variegata* + *Pennisetum purpureum*

Source: Dhyani et al. (2009) and modified by the authors of this article.

The agro-climatic zone-wise agroforestry system has been mentioned in Table 3. Some of the most prevalent agroforestry systems in India have been discussed below.

Agri-silviculture system: In this system, crops (cereals, pulses, oilseeds, vegetables, and aromatic plants) are grown with tree crops concurrently on the same piece of land. It is the most prominent agroforestry system in India. Tree components give fodder, fuel, or timber, including green-leaf manure. It is ideal for class IV soils of drylands with an annual rainfall of ~750 mm. Hedgerow intercropping (alley cropping) is a classic example of the agri-silviculture system. Wind breaks and shelterbelts also come under the agri-silviculture system. Cultivation of wheat + poplar is a prominent agroforestry system in the Indo-Gangetic plains of India (Chavan et al., 2022).

Agri-horticulture system: In this system tree component is a fruit tree. It is also called as food *cum* fruit system. In this system, short-duration arable crops are grown in the interspaces of fruit trees. Some of the fruit trees that can be considered are guava, pomegranate, custard apple, sapota, and mango. Pulses are the important arable crops for this system. This is the second most widely practiced agroforestry system in India. For example, the cultivation of cowpea + sapota is one kind of agri-horticulture system (Jinger et al., 2022a).

Agri-silvi-horticulture system: It is the integration of agri-silviculture and the horti-silviculture system. Integration of horticultural plant species provides regular income to the farmers in addition to the production from crops during the early stages of tree establishment, whereas silviculture species provide income in the later stage sustaining long-term productivity (Kaushik et al., 2014). The system has been advocated to arrest degradation and increase the fertility status of soil and enhance yields. Productivity in the agri-silvi-horticultural system is comparatively higher than the productivity of sole agriculture (Kaushik et al., 2017).

Silvi-pasture system: The production of woody plants combined with grasses is referred to silvipasture system. This system is primarily meant for augmenting the scarce fodder supply to livestock, or it may be practiced for timber, fuel wood, and improving the soil. In marginal lands (class IV onwards), this system enhances sustainability through resource conservation and its efficient use, improvement in soil health, and by linking agriculture with cattle. Cultivation of *Leucaena leucocephala* and *Gliricidia sepium*-based silvi-pasture system is most prevalent in India (Chauhan et al., 2014).

Horti-pasture system: In this system, fruit trees are grown with fodder grasses concurrently on the same piece of land. Guava, aonla, custard apple, ber suits well in the horti-pasture system with grasses such as *Cenchrus ciliaris, Cenchrus setigerus, Panicum antidotale, Dicanthium annulatum*, *Chloris gayana*, and legumes such as *Stylosanthes hamata*, *Stylosanthes scarab*, and *Macroptilum artopurpuream*. Cultivation of aonla + *Cenchrus ciliaris* is widely practiced horti-pasture systems in arid and semiarid regions of India (Kumar et al., 2015).

Agri-silvi-pasture system: In this system, crops and grasses are intercropped with woody components on the same piece of land. This system is practiced for food production and soil conservation and provides fodder and fuel. This system is recommended for highland humid tropics. It may be a tree-livestock crop mix around a homestead, wood-hedgerow for browsing, green-leaf manure, and soil conservation (Rao et al., 2018).

Agroforestry nexus land rehabilitation

Agroforestry can be considered a versatile panacea for multiple problems being faced by the agriculture sector. Agroforestry has huge potential to mitigate the impacts of climate change by sequestering atmospheric carbon in their biomass and soil. The average carbon sequestered by agroforestry practices has been estimated to be 9, 21, 50, and 63 Mg C ha^{-1} in semiarid, sub-humid, humid, and temperate regions (Murthy et al., 2013). Moreover, a dense canopy spread in an agroforestry system reduces the intensity of rainfall by reducing the kinetic energy of raindrops. Thereafter, water moves very slowly from the tree-crop (agroforestry) structure to the soil. Hence, runoff velocity is reduced, and the soil gets more opportunity time to absorb the water. Thus, ultimately soil erosion is reduced (Figure 2). Furthermore, the agroforestry system has tremendous potential to produce a huge quantity of leaf litter which also acts as mulch and also forms humus after decomposition and improves soil's physical, chemical, and biological properties (Jama et al., 2006). Soil improvement in agroforestry systems is linked to biological nitrogen fixation, recycling of nutrients from deeper layers to the surface soil, building up soil organic matter (SOM) from aboveground and below-ground parts of plants, increasing soil microbial activity, improving soil enzyme activity, and enhancing the activity of arbuscular mycorrhizal fungi (Dollinger and Jose, 2018). The different direct and indirect benefits received from agroforestry has mentioned in Figure 3. Moreover, the carbon sequestration potential and food production potential of different agroforestry systems in agro-climatic zones of India have been mentioned in Table 4.

Agroforestry for rehabilitation of degraded lands

By 2050, India wants to have 53 M ha under agroforestry, which will be accomplished by reclaiming fallows, cultivable fallows, pastures, groves, and problematic soils (Dhyani and Handa, 2013). In India, agroforestry practices are an important component in the various river rejuvenation programs like Namami Gange, Green India Mission, National Highway Mission, Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), and Mahatma Gandhi National Rural Employment Guarantee Act (MNREGA). Several research Institutes like the Indian Council of Agricultural Research (ICAR), Forest Research Institute (FRI), Council of Scientific and Industrial Research (CSIR), State Agricultural Universities (SAUs), and Krishi Vigyan Kendra (KVKs) have developed cost-effective agroforestry technologies for the rehabilitation of degraded lands. ICAR-CAFRI and AICRPAF published a summary on *Agroforestry technologies for different agroclimatic zones of Country*, whereas it consists of 84 grassroots levels farmers adopted technologies developed by 26 AICRPAF centers from five different agroclimatic regions of the country (Chaturvedi et al., 2016). FRI has also come up with various river rejuvenation technologies for the rehabilitation of basin areas. The different agroforestry technologies for lands affected by soil erosion (water and wind), physical (mining and industrial waste and waterlogged lands), chemical (saline, sodic, and acidic soils), and biologically degraded lands due to depletion of SOM, reduction in soil fauna, and emission of green house gases (GHGs) are discussed below:

Water eroded lands

One of the main reasons for the degradation of the land is water-induced soil erosion. A moderate (>10 Mg ha^{-1} year^{-1}) to extremely severe (>80 Mg ha^{-1} year^{-1}) intensity of water erosion affects ~68.4% (83 M ha) of the total degraded land (120.7 M ha) in India. The main danger to soil quality posed by runoff water is water erosion. Loss of organic carbon, nitrogen imbalance, compaction, a decrease in soil biodiversity, and pesticide and heavy metal contamination are the results. The lands affected by water erosion can be categorized into three categories: (a) degraded sloping lands, (b) gully and ravine lands, and (c) shifting cultivation lands.

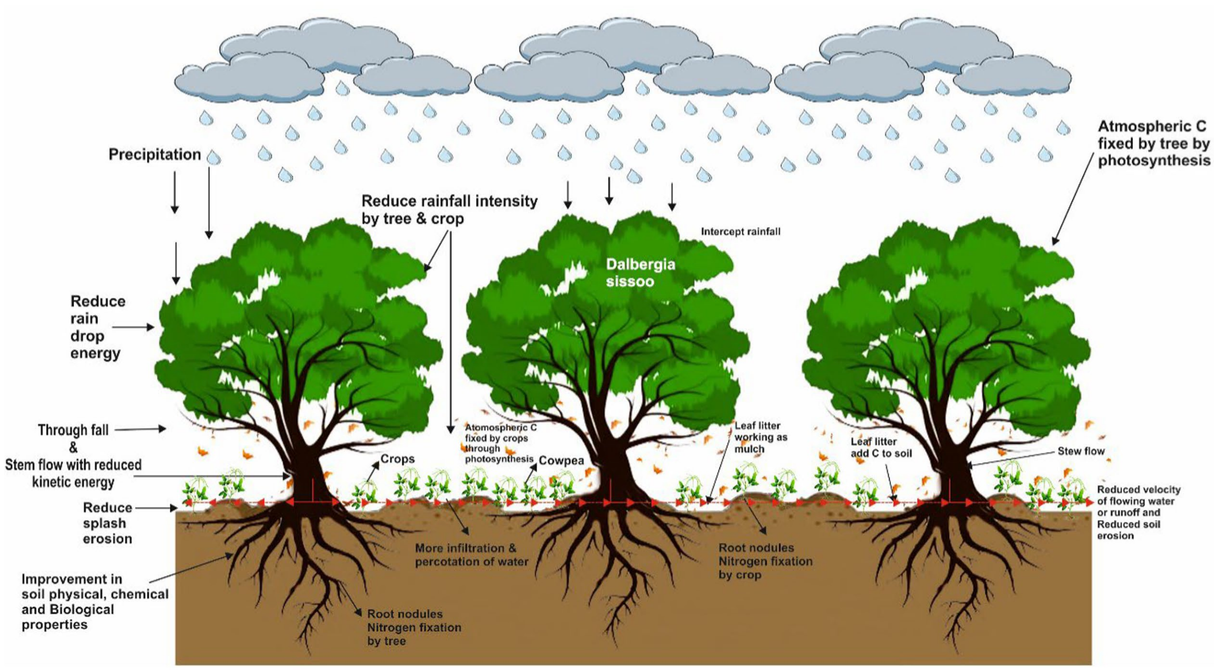

FIGURE 2
Agroforestry system and its impact on carbon sequestration, soil erosion, and soil fertility.

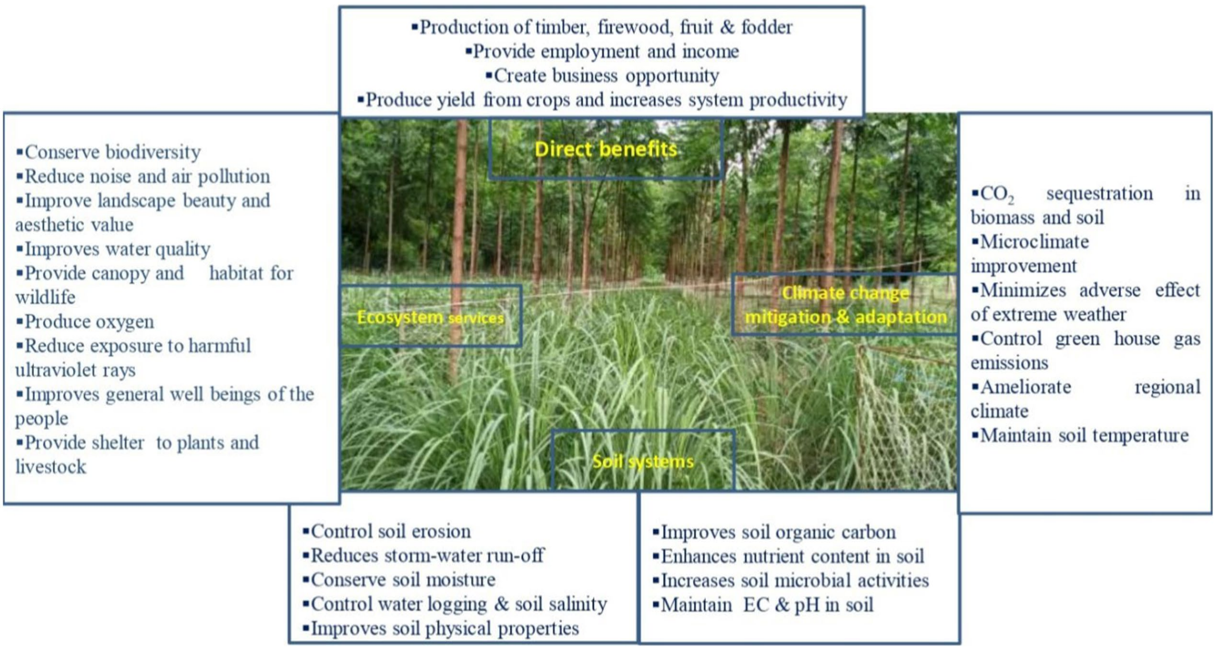

FIGURE 3
Influence of agroforestry on various direct and indirect benefits in the degraded lands.

The importance of trees in controlling soil erosion is widely accepted. In agroforestry, tree canopy checks soil erosion mainly by intercepting rainfall, thereby reducing the impact of raindrops and decreasing their erosive capacity (Kaushal et al., 2017). Litter helps in producing water-stable aggregates, thereby reducing the surface runoff volume. Roots and stems restrict sediments from moving down the slope and help water infiltrate. Shallow landslides are prevented by deep tree roots that stabilize slopes. Vegetation affects water and sediment fluxes over the long run by boosting soil water infiltration and soil aggregate stability and cohesiveness (Zuazo and Pleguezuelo, 2008). The most widely utilized agroforestry techniques for erosion management include windbreaks and shelterbelts, hedgerow (alley) cropping, multilayer tree gardens, home gardens, plantation crop combinations, and multilayer tree gardens (Young, 1997). According to McDonald et al. (2002), agroforestry

TABLE 4 Carbon sequestration and food production potential different most prevalent agroforestry systems in agro-climatic zones of India.

S. No.	Agro-climatic zones	Agroforestry system	Carbon sequestration potential (Mg C ha^{-1} year^{-1})	Food production potential (Mg ha^{-1} year^{-1})	References
1.	Western Himalayan Region	Agri-horticulture (*Prunus armeniaca* + *Ocimum sanctum*)	1.80	11.0 (Apricot) 1.90 (Tulsi)	Handa et al. (2020)
		(*Prunus persica* + *Ocimum sanctum*)	2.0	20.5 (Peach) 1.90 (Tulsi)	
2.	Eastern Himalayan Region	Silvi-pasture (*Morus alba* + *Setaria anceps* grass)	1.55	8 (Tree fodder) 24 (Green forage)	Handa et al. (2020)
3.	Lower Gangetic Plains Region	Agri-silviculture (*Eucalyptus tereticornis* + rice-wheat)	10.7	3.5 (Rice) 3.2 (Wheat)	Sirohi and Bnagrawa (2017)
4.	Middle Gangetic Plains Region	Agri-silviculture *Tectona grandis* + sorghum/groundnut	2.32	1.5 (Sorghum) 1.2 (Groundnut)	Handa et al. (2020)
5.	Upper Gangetic Plains Region	Agri-silviculture *Dalbergia sisso* + mustard	2.83	0.75 (mustard)	Newaj et al. (2012)
6.	Trans-Gangetic plains Region	Agri-silviculture *Populus deltoides* + wheat/potato/turmeric	9.12	3.26 (Wheat) 13.1 (Potato) 9.1 (turmeric)	Chavan et al. (2022)
7.	Eastern Plateau & Hills Region	Agri-silviculture *Albizia procera* + wheat	5.70	3.21 (Wheat)	Newaj et al. (2012)
8.	Central Plateau & Hill Region	Agri-silviculture (Acacia + greengram-mustard)	3.70	0.75 (Greengram) 1.3 (Mustard)	Newaj et al. (2008)
9.	Western Plateau & Hills Region	Agri-silviculture (*Ailanthus excelsa* + cowpea-mustard)	9.64	0.47 (cowpea) 0.75 (mustard)	Handa et al. (2019, 2020)
10.	Southern Plateau and Hills Region	Silvipasture system (*Leucaena leucocephala* + *Gliricidia sepium Stylosanthes hamata*)	23.2	9.20 (Leucaena) 18.5 (Gliricidia) 5.84 (Grass)	Handa et al. (2019)
11.	East Coast plains & Hills region	Horti-silviculture *Acacia mangium* + pineapple	5.51	7.65 (Pineapple)	Handa et al. (2019)
12.	West Coast Plains & Ghats Region	Agri-silvi-horticulture (*Artocarpus heterophyllus* + *Acacia auriculiformis* + black pepper)	9.90	30 (Jack fruit)	Kunhamu et al. (2012)
			11.3	1.91–2.56 (black pepper)	
13.	Gujarat Plains & Hills Regions	Silvo-aromatic (*Melia dubia* + lemon grass)	20–25	11 (lemon grass)	Jinger et al. (2022c)
14.	Western Dry Region	Silvipasture system (*Ailanthus* + *Cenchrus ciliaris*/ *Panicum antidotale*)	9.64	5–6 (Fodder)	Handa et al. (2020)
15.	The Island Regions	Horti-pasture (*Cocos nucifera* + *Calliandra calothyrsus*)	3.50	16,751 (coconuts ha^{-1}) 5 (Dry forage)	Joy et al. (2019)

reduced soil erosion by 21 times and surface runoff by seven times compared to control soils. The retention, infiltration, and storage of rainfall-induced overland flow are improved by adding tree leaf litter, its subsequent decomposition in the soil, and the activities of trees' roots (Dass et al., 2011). The different agroforestry models/technologies developed for lands affected by soil erosion are as below.

Degraded sloping lands

In addition, mudslides, landslides, and other gravity erosion processes are more likely to occur in steeper terrain. Longer, steeper slopes are more prone to erosion during heavy rains than shorter, less steep slopes because they lack sufficient plant cover. Various agroforestry models have been developed and evaluated for water-eroded lands in the northwestern and northeastern Himalayan regions (Kaushal et al., 2021a). The best filter strips to stop erosion and boost agricultural output in marginal lands are vegetative barriers made of hedgerows of trees such as *Leucaena* and *Gliricidia* and grasses. In various land-use regimes, hedgerows are very helpful in preventing the loss of nutrients and organic carbon during the erosion processes. Hedgerows' blockage caused soil and nutrients to accumulate close to the biological barrier system. According to Lenka et al. (2012), grass filter strips and hedgerows (Indigofera) have a great capacity to conserve soil organic carbon (SOC) (43%), as well as accessible nitrogen (56%), phosphorus (54%), and potassium (48%) in the soil. According to Hombegowda et al. (2020), under *Gliricidia* and *Leucaena*-based hedgerows, respectively, the configuration of the land slope reduced by 0.41 and 0.27 degrees year^{-1}, showing the deposition of eroded soils on the lower slope side and the consequent decrease in the land slope.

On degraded slopes, silvipasture systems have proven effective (Chaturvedi et al., 2014). In the Shiwalik foothills, *Eucalyptus tereticornis* and *Eulaliopsis binata* (@ 2,500 trees ha^{-1}) were grown in paired rows with understorey grass planted at 50-cm × 50-cm spacing. This method prevented soil loss and produced an annual return of approximately Rs. 4,000 (50 USD) ha^{-1} year^{-1} from commercial grass alone, in addition to returns from the *Eucalyptus*, which made the crop more profitable (Sharda and Venkateswarlu, 2007). When combined with *Chrysopogon fulvus* (gorda) and *Eulaliopsis binate* (bhabar) in the Doon Valley, the plant's *Albizia lebbek* (siris), *Grewia optiva* (bhimal), *Bauhinia purpurea* (kachnar), and *Leucaena leucocephala* (subabul) were found to be promising. The average yearly production of savanna pasture systems is 8–10 Mg ha^{-1}, consisting of 4.5–5.0 Mg ha^{-1} of grass-based fodder, 1.5–2.0 Mg ha^{-1} of leaf fodder from tree loppings, and 2.0–2.5 Mg ha^{-1} of fuelwood from the lopped branches (Raizada and Singh, 2010).

On degraded sloping lands, the plantation of trees, along with trenching, is useful for improving the survival and growth of plantations. The trenches effectively stop soil erosion and improve the soil moisture regime by breaking the slope and lowering the surface runoff velocity. According to Kaushal et al. (2021a), semicircular ditches and *Dendrocalamus. hamiltonii* species can be a successful land restoration approach on degraded sloping soils in the Himalayan foothills. Comparing the semicircular trenches to the control treatment, the soil moisture was 16% greater (without trenches). Runoff and soil loss were drastically reduced with bamboo + trenching treatment. After the 5th year of the plantation, no runoff or soil loss was seen, demonstrating the effectiveness of bamboo and *in situ* water-conserving techniques in preventing soil erosion. In the Eastern Ghats, the *Gliricidia* + Trench and *Leucaena* + Trench planting systems, respectively, boosted the efficiency of SOC and accessible NPK by 44%, 63%, 56%, and 33%, 46%, 44%, 42% (Hombegowda et al., 2020). According to Satapathy (2005), mixed land-use schemes that included bench terraces and contour trenches effectively retained 90%–100% of the yearly rainfall and mimicked the impacts of a natural forest in the northeastern region. Base flow accounted for 70%–90% of the water yields in watersheds with continuous stream flow characteristics. The watershed that had been subjected to jhum (shifting) cultivation produced the greatest peak runoff, whereas the watershed that had been left to its natural vegetation produced the least peak runoff.

In the Himalayan area, agri-horticulture is the most significant system in terms of productivity, financial rewards to farmers, and preferences on sloping slopes. As an economically feasible strategy for rehabilitating marginal lands in the Shiwalik region, intercropping of guar, cowpea, or pearl millet with peach, turmeric with papaya, *Chrysopogon fulvus* or *Pennisetum purpureum* (Napier grass) with aonla or ber, has been discovered. With pigeon peas, Aonla produced the largest production of 86-kg fruits tree^{-1}; however, the output was decreased by 17% and 23% with *Chrysopogon* and Napier grass, respectively (Sharda and Venkateswarlu, 2007). Runoff was 8.0%, 13.1%, and 18.6% for aonla + *Chrysopogon fulvus*, aonla + hybrid Napier, and aonla + perennial pigeon pea, respectively, over control during a period of 10 years (pure aonla). *Chrysopogon*, Napier, and pigeon pea were the most successful intercrops at reducing soil loss, with reductions of 81, 56, and 25% over sole aonla. By contrast to runoff, less sediment was lost during the post-bearing phases (Yadav et al., 2005). The cowpea-toria sequence was shown to be very profitable, with a gross revenue of Rs. 16,850 ha^{-1} (210 USD), and successful in preserving soil and water, according to an analysis of mango-based agri-horticulture systems (Rathore et al., 2012).

Gully and ravine lands

In dry and semi-arid locations, erosion by water is a serious issue that results in gullies and ravines. The use of gullies by land capacity classes, soil and water conservation measures, and permanent plant cover through afforestation or agroforestry systems are all necessary for the revival of ravine lands (Chaturvedi et al., 2014). The newly planted trees reduce soil and nutrient loss from these lands while providing risk protection against the uncertainties of agricultural production in the tough circumstances of ravine regions (Soni et al., 2018). In the ravine region, the silvi-pastoral system has been proven to be quite successful. Several significant grass species are useful for enhancing the fodder availability in the ravine regions, including *Pennisetum purpureum, Brachiaria mutica, Cenchrus ciliaris, Cenchrus setigerus, Panicum antidotale,* and *Panicum maximum* (Chaturvedi et al., 2011). Plantations of *Acacia nilotica* and *Acacia tortilis* with *Cenchrus ciliaris* produced 28.7 Mg ha^{-1} and 27 Mg ha^{-1} of fuel wood, respectively, at a spacing of 3 m × 3 m on the top, slopes, and bottom of ravines. Under *Acacia nilotica* and *Acacia tortilis*, the mean annual pasturage yield varied from 1.52 Mg ha^{-1} year^{-1} to 2.06 Mg ha^{-1} year^{-1}, respectively (Kurothe et al., 2018).

For ravine areas, fruit plants that can endure moisture stress are appropriate. In humps and gully beds, fruit trees, including lemon, mango, ber, and aonla are planted alongside agricultural products. Agroforestry and soil water conservation practices, according to Kumar et al. (2019), boosted the carbon storage and sequestration capacity in semi-arid, climate change-vulnerable ravine landscapes while also increasing agro-ecosystem resilience to harsh weather. According to Kumar et al. (2020), a sapota-based agri-horticulture system with bench terraces and trenches reduced runoff by 16%–34% and soil loss by 15%–25% when compared to sapota on the slope. In a similar vein, Jinger et al. (2022a) found that using an agroforestry system with cowpea, castor, and sapota reduced soil loss and runoff overall by 37.7% and 19.1%, respectively, when compared to using only one crop. The agroforestry system, which boosted system production by 162% and 81.9%, respectively, above the sole crop and sole tree plantation, yielded the highest system productivity.

Dendrocalamus strictus, a bamboo species, holds great promise for preserving soil and maximizing the use of gullies and ravine areas for agricultural purposes (Rao et al., 2012). Bamboo roots effectively increase infiltration, decrease runoff, and safeguard soil from additional gully bed expansion (Singh et al., 2015; Kaushal et al., 2020, 2021b). A silvopasture system based on Anjan (*Cenchrus ciliaris*) and bamboo (*D. strictus*) grass has been created to increase the productivity of ravines. More than 80% of rainwater can be absorbed by this system, which also reduces soil and nutrient losses by 90% and 70%, respectively. These interventions gave an average annual net return varying from USD 814 to Rs. 1,130 ha^{-1} and a cost–benefit ratio varying from 1.96 to 2.09. *Melia dubia* + dragon fruit and *Melia dubia* + lemon grass cultivation along with soil moisture conservation practices has resulted in better fruit yield of dragon fruit and biomass yield of *Melia dubia* and lemon grass compared to control besides conservation of soil and water in Mahi ravines of Central Gujarat (Jinger et al., 2020, 2021; Kakade et al., 2020).

Shifting cultivation lands

Approximately 7.60 M ha of shifting agriculture, or jhum cultivation, is performed in India's eastern and northeastern areas (Bhat et al., 2022). Because of the diminished jhum cycle brought on by strain from a growing human population, significant soil erosion, low productivity, and loss of soil fertility, shifting farming has become unsustainable (Markose and Jayappa, 2016). Agroforestry systems with many stories and improved fallows are essential for rehabilitating regions damaged by shifting farming. Fast-growing, nitrogen-fixing trees are cultivated during the fallow period in an upgraded fallows system. Improved fallows improve soil qualities such as organic matter, greater aggregates stabilizing soil, higher infiltration rate, and carbon sequestration in addition to increasing crop productivity (Chirwa et al., 2004). According to reports, soil in planted fallows contains larger pores and more macropores due to better aggregation and channels formed by dead and decomposing roots (Nyamadzawo et al., 2008). With the aid of the region's natural resources, suitable alternative land-use systems for agriculture, horticulture, forestry, and agroforestry have been developed with almost equivalent hydrological behavior under the natural system. For the general development of these places, an integrated farming system strategy comprising fruit and forest trees, arable crops, livestock, fisheries, and poultry with sufficient conservation measures for natural resources has been determined to be suitable. In addition to preserving and safeguarding the hill soils, agri-horticultural systems that combine the production of ginger with fruit trees like mandarin and guava be successful. Pineapple is commonly connected with multi-use trees that are arranged in paired rows on a hillside. According to Saha et al. (2012), agri-horti-silvi-pastoral farming systems and bench terrace farming may successfully control runoff and soil losses. In mixed land-use systems with soil water conservation features like bench terraces and contour trenches kept because these systems resemble natural forests, 90%–100% of the yearly rainfall has reportedly been found to be retained. According to some reports, contour hedgerow technology (bio-terracing) is more cost-effective than bench terraces built using the cut-and-fill method across slopes. Saha et al. (2005) found that multi-storied agroforestry systems (3.06) and silvi-horti-pastoral (3.07) had low erosion ratio values, indicating that these systems were best suited for conserving soil and water in the hilly habitat. When compared to traditional farmers' practices of growing finger millet, a mixed plantation of *Moringa oleifera, Gliricidia sepium, Zingiber officinale, and Cajanus cajan* in East India reduced runoff and soil loss by 8.26% and 3.45 Mg ha^{-1}, respectively, while increasing SOC, P, and K by 74%, 64%, and 66%, respectively. Drumstick pod output increased 24%–27% as a result of the multipurpose *Gliricidia* hedgerow approach (Jakhar et al., 2017). Table 5 lists the agroforestry systems for various degraded soils. To check runoff and soil losses, alley cropping (hedgerow intercropping) has also been recommended as an alternative to shifting cultivation. The hedge serves as a barrier for checking the movement of soil and water along the slope and contributes to soil conservation (Sharda and Mandal, 2018). Continuously soil deposition near hedges leads to the formation of biological terrace-like structures in the long term. *Leucaena leucocephala and Cassia siamea* are the most recommended species for alley-cropping systems in the northeastern region of India (Kaushal et al., 2021a). Improved animal-based and horticulture-based integrated farming system (IFS) models were found to reduce soil erosion (34%–48%) and loss of SOM (26%–51%), N (33%–45%), P (19%–54%), and K (27%–51%) compared to the traditional shifting cultivation system in Nagaland, India (Chatterjee et al., 2021).

Wind eroded lands

After water erosion and vegetation degradation, wind erosion is the third most contributing factor for land degradation in India, covering 18.19 M ha, i.e., ~6% of the total geographical area. The causes, impact, and control of wind erosion are summarized in Figure 2. In dry and semi-arid areas, such as the states of Rajasthan, Haryana, Gujarat, and Punjab, wind erosion can range from mild to severe. In addition, it is common in coastal locations with sandy soils predominating and in the chilly desert regions of Leh (Jammu & Kashmir), which are both in the far northwestern part of India (Singh D. V. et al., 2017; Singh C. et al., 2017). In drylands, erosion by wind is one of the principal processes associated with land degradation covering 33%–37% of the continental areas of the planet (Sivakumar et al., 1998) and is of major concern for policymakers and land managers (Duniway et al., 2019).

Agroforestry for wind-eroded lands

The most widely used agroforestry technologies to restore wind-eroded lands are stabilizing dunes, windbreaks, shelterbelts, alley-cropping, and silvopastoral systems (Figure 2). According to CAZRI (2015), covering the space beneath trees, providing a surface cover of grasses, and protecting them from biotic intervention are the most crucial steps in stabilizing sand dunes. On the windward side of the dune, small windbreaks are built in strips or chessboard patterns of 5 m each. Locally accessible brushwood species such as *Leptadenia pyrotechnica* (Khimp), *Aerua tomentosa*, *Ziziphus nummularia* (Pala), *Crotalaria burhia* (Sania), and *Calligonum polygonides* (Phog) are constructed upside down for the purpose of producing micro-wind barriers (Singh D. V. et al., 2017; Singh C. et al., 2017). Mulching is done in April and May to slow down the speed of the wind and stop sand from moving. To build the plants in the trench and create a dry hedge, sand is removed to a depth of 25 cm along the mulching line. Before the start of the rain, trees, bushes, and grasses are planted (Luna, 2006). After the rains have started, 1 × 1 m of grass is sown. During the monsoon, seeds of grasses and leguminous plants are sown on the side that receives micro-wind breaks and is mixed with clay and sodium arsenate. Many different types of grasses are employed, including *Lasiurus sindicus, Panicum turgidum, P. antidotale, Saccharum munja, Cenchrus ciliaris, C. setigerus, Dichanthium annulatum*, and *Sachharum bengalense*. The vegetation used to stabilize sand dunes is extremely drought resistant and has deep roots that may draw rainwater from shallower soil layers. The most effective combination of trees for stabilizing sand dunes has been determined to be *Acacia tortilis, Acacia jacquimontii, Acacia leucophloea, Acacia senegal, Azadirachta indica, Balanites roxburghii, Prosopis cineraria, P. juliflora*, and *Holoptelia integrifolia* (Singh D. V. et al., 2017; Singh C. et al., 2017). Sand dune stabilization technology helped in fixing up 0.4 M ha of sand dunes with the help of the Rajasthan state forest department (Harsh and Tewari, 1993).

TABLE 5 Agroforestry systems developed for sloping, gully, and shifting cultivated lands in India.

Type of degraded land	Location	Agroforestry system	Impact	Reference
Degraded sloping land	North-East India	Hedgerow cropping	Reduced soil loss and runoff by 94% and 78%, respectively	Saha et al. (2012)
	Dehradun	Silvipasture system	No soil loss with an annual return of about Rs. 4,000 ha^{-1} $year^{-1}$ from commercial grass alone besides additional returns from Eucalyptus.	Sharda and Venkateswarlu (2007)
	Shivalik hills	Horti-pasture system	*Emblica officinalis* + *Chrysopogon fulvus* Horti-pasture system saved water and soil by 4.9–30.7 cm and 862–2,818 kg ha^{-1}	Prasad et al. (2012)
	Karnataka	Ley farming (Vegetative barriers)	*Cenchrus ciliaris* and *Cymbopogon martini* reduced the runoff by 38% and soil loss by 16%	Ramajayam et al. (2007)
	Kashmir	Silvi-agriculture	Reduced scorching heat and the same time reduced soil erosion, besides increased crop production	Mughal and Makaya (2000)
Gullied and ravine lands	Gujarat	Agri-horticulture system with soil moisture conservation practices	They revealed that sapota with trenches and bench terraces reduced runoff by 16%–34% and soil loss by 15%–25%	Kumar et al. (2020)
	Gujarat	Agroforestry system of cowpea + castor + sapota	Reduced total soil loss and runoff by 37.7 and 19.1% and system productivity increased by 81.9% compared to sole tree plantation	Jinger et al. (2022a)
	Uttar Pradesh	Agri-horticulture system	Recorded higher yield of Ber, pearl millet, wheat and fuel wood	Prakash et al. (2011)
	Rajasthan	Alley cropping	Higher yield, land equivalent ratio and soil organic carbon were recorded in *Leucaena*-based alley-cropping systems	Dhyani et al. (2007)
Shifting cultivation land	North-East India	Multipurpose tree plantation (fast-growing nitrogen-fixing trees) in fallows	Reduction in bulk density by 15.9% and erosion ratio by 39.5%, and increase in SOC by 96.2%, aggregate stability by 24.0%, porosity by 10.9%, and available soil moisture by 33.2%	Saha et al. (2012)
	Odisha	Alley cropping	The runoff and soil loss was reduced by 23%–32% and 49%–52%, respectively	Adhikary et al. (2017)
	East India	Gliricidia sepium hedgerow and grass filter strip	The runoff and soil loss was reduced by 32 and 35%, respectively	Lenka et al. (2012)

Raising shelterbelts around the agricultural fields also minimizes wind hazards and increases farm productivity through the moderation of micro-climate (Prasad et al., 2009). The technology involves raising strips of vegetation composed of trees and local shrub wood material against the prevailing wind direction. Shelterbelt plantation helps fix the movement of sand from dunes and provides multiple products to farmers. It was reported that almost 84% of farmers have received the benefits of better groundwater availability and improved soil texture for the production of crops by raising shelterbelts (The Energy and Resources Institute, 2016). In the IGNP (Indira Gandhi Nahar Pariyojna) area of Jaisalmer (W. Rajasthan), the assessment of efficiency of single- and double-row shelterbelts of *Dalbergia sissoo* revealed that the double-row shelterbelt of 15–20 years of age having 8–10 m height hold great promise for moderating micro-climate and providing effective shelter to crops against wind-borne hazards in arid areas. Shelterbelts have improved soil characteristics and modified air temperature (Prasad et al., 2009). Another study reported that the shelterbelts increased net returns from agricultural production by 430.8% in the net returns due to shelterbelt plantation, in which shelterbelt technology has contributed ~399% (Gajja et al., 2008).

Silvi-pastoral systems are other important agroforestry systems in wind-eroded areas. In addition, providing nutritional fodder to livestock protects them from hot and warm winds, improving overall animal health and productivity (Atangana et al., 2014). There are several examples where different agroforestry systems have contributed to minimizing erosion and enhancing farm productivity, soil fertility, and ameliorated micro-climate (Table 6). With all these efforts sand dune

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TABLE 6 Different agroforestry systems for wind-eroded areas and their impact on controlling erosion.

Agroforestry system		Species	Impact	Reference
Sand dune stabilization	Karnataka	*Canavalia cathartica, Canavalia maritima*	Act as green manure, mulch, cover crop, pasture, fodder, oil and medicinal value	Sridhar and Bhagya (2007)
	Thar desert (Rajasthan)	*Calligonum polygonoides, Lasiurus sindicus, Calotropis procera*	Significant reduction in soil erosion through wind due to because grasses had massive network of underground roots, which works as effective "sand binders"	Chauhan (2003)
Shelterbelts	Karnataka	Bamboo	Sorghum gave higher yield of 4.15 Mg ha^{-1} with a shelterbelt of compared with 3.72 Mg ha^{-1} without a shelterbelt	Reddy and Kulkarni (1978)
	Thar desert (Rajasthan)	*Prosopis juliflora, Acacia tortilis, Cassia siamea*	Brought about 50% reductions in wind erosion. Most effective in conserving soil due to thicker branching and more leafiness and, therefore, lesser air permeability provided by this shelterbelt	Chauhan (2003)
	Jaisalmer and Bikaner (Rajasthan)	*Acacia tortilis Tecomella undulata*	Reduced sand deposition by 0.513 m^3 and 1.023 m^3 per running meter length of the canal, respectively, saved de-silting cost by Rs. 6,156–Rs 12,276 per kilometer in one year	Upadhyaya (1991)
Micro-windbreaks	North Western part of Indian desert	*Acacia tortilis, Prosopis juliflora, Calligonum polygonoides, Cassia angustifolia, Cenchrus ciliaris*	Improvement of soil conditions and controls the sand drift when the seedlings attain greater height	Singh and Rathod (2002)
Shelterbelts	Western Rajasthan	*Acacia tortilis, Eucalyptus camaldulensis, Dalbergia sissoo, Tecomella undulata*	Enhanced soil organic carbon (0.11%–0.46%) and reduced daily air temperature (3.5°C–8°C) in sheltered area	Prasad et al. (2013)
Live fencing	Bikaner (Rajasthan)	*Calligonum polygonoides, Acacia jacquimontii, Acacia senegal*	Live fences act as windbreaks, reducing wind stress on livestock or crop plants, drying of soils and wind erosion. Add nitrogen and organic matter thus build up humus in the soil through breakdown of leaf litter and root hairs	Soni et al. (2016)
Silvo-pastoral system	Jodhpur (Rajasthan)	Strip cropping of *Cenchrus ciliaris* or *Lasiurus sindicus* with the *Lablab purpureus* in association with *Colophospermum mopane* or *Hardwickia binate*	Improved fodder yield, soil binding capacity of soil and reduced wind erosion	Patidar et al. (2008)
Horti-pasture	Jodhpur (Rajasthan)	*Ziziphus rotundifolia* and *C. ciliaris*	Sustain 554 Tharparkar cattle days ha^{-1} with 60% pasture utilization along with soil conservation	Narain and Bhati (2004)
Silvo-pastoral system	Kachchh (Gujarat)	*Acacia* + *C. ciliaris, Acacia* + *C. setigerus*	Sequestered carbon from 60.1 to 6.82 Mg C ha^{-1} as well as reduction in wind erosion due to soil cover of grasses	Shamsudheen et al. (2014)
Multipurpose tree plantation	Barmer (Rajasthan)	*Acacia senegal*	Improvement in soil fertility by nitrogen fixation and 12,000 trees were treated through CAZRI gum inducer which resulted in exudation of 5.4 Mg of gum Arabic and farmers earned INR 2.7 million from the sale of gum	Tewari et al. (2014)

(Continued)

TABLE 6 (Continued)

Agroforestry system		Species	Impact	Reference
Silvo-pastoral system	Bhuj (Gujarat)	*Acacia tortilis, Azadirachta indica, C. ciliaris, C. setigerus*	18% area under culturable wasteland improved due to improvement in soil physical and chemical properties by silvo-pastoral system	Shamsudheen et al. (2009)
Silvo-pastoral system	Jhansi (Uttar Pradesh)	*Acacia tortilis, C. ciliaris*	*A. tortilis* + *C. ciliaris* maintained higher soil moisture, organic carbon content and available N, P, and K for the longer period in the soil	Mishra et al. (2010)
Silvo-pastoral system	Jhansi (Uttar Pradesh)	Multipurpose tree with *D. annulatum*	Average soil loss from a silvopasture system recorded only 0.9 $Mg\,ha^{-1}$ but it was recorded 12–43 $Mg\,ha^{-1}$ in deforested black soil, 4–10 $Mg\,ha^{-1}$ in red soil and 3.2 $Mg\,ha^{-1}$ from natural grassland	Kalloo (2003)
Grass based strip cropping	Western Rajasthan	*C. ciliaris* and *L. sindicus*	Grasseshelpd in reducing wind speed due to vegetation cover and soil binding especially in the top 15 cm soil profile due to their fine root systems and thus controls the soil erosion against wind	Soni et al. (2006, 2013)
Silvo-pastoral system	Kurukshetra (Haryana)	*L. leucocephala, C. ciliaris S. hamata*	Increase in organic carbon of 1.7–2.3 times compared to a control	Kaur et al. (2002a)
Silvo-pastoral system	Kurukshetra (Haryana)	*A. nilotica, D. sissoo, P. juliflora, D. bipinnata*	About 77%–89% of the net annual N uptake by the vegetation was returned to the soil through litter fall and turnover of fine roots. Thus improved soil fertility and reduced soil erosion	Kaur et al. (2002b)
Agri-silviculture	North Western Gujarat	*Azadirachta indica, Ailanthus excelsa*, cowpea, green gram, cluster bean and sesame	Fetched 25.7%–59.3% more income than sole cropping and also improved soil organic carbon along with catering diverse need of farmer *viz.* fodder, fuel wood and timber	Patel et al. (2008)
Bio-fencing	Ladakh (Cold desert)	*Hippophae* spp. (Sea buckthorn)	Bio-fencing of this plant being thorny in nature protects crops from stray animals. Its multipurpose utility as a nitrogen fixer, check against soil erosion, conservation of moisture, source of fuel wood and indigenous drug (rich source of vitamin C) makes it a promising plant for eco-economic rehabilitation of the region	Khosla et al. (2018)

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area has reduced by 12% between 1980 and till date. The portion of western Rajasthan that is impacted by wind erosion has shrunk by 3%. The region has seen a rise in the net sown area, a decrease in culturable wastelands, and an increase in total crop area. This impact has come from using different agroforestry techniques for combating wind erosion in the area (Moharana et al., 2018).

Physical land degradation

It is a degradation of the soil's structure, hampering its role and ecosystem services. It is mostly occurred due to indiscriminate anthropogenic activities, uncontrolled or faulty agriculture practices, climate change (flood), and industrial development. It may become a threat to meeting the visions of the SDGs. Mining (mined land), industrial wastewater, and waterlogged lands are the major form of physical land degradation affecting 1.07-M ha of land in India. Different agroforestry systems have been developed for rehabilitating physical land degradation.

Mined area

The mining sector, which plays an essential role in national economic growth, involves more than 20,000 known mineral deposits and provides the bulk of employment and job creation of ~5,60,000 individuals daily in India. India's mining sector is large, with 9,200 mines spread across 11 states producing 84 different minerals, comprising four fuel, 11 metallic, 49 non-metallic industrial, and 20 minor minerals (Ministry of Mines, 2018), according to Das et al. (2018), ~3,100 mines operating in India. It is estimated that ~12,000 stone crusher units are operating in India (Patil, 2001). Although it contributes 10%–12% of GDP to India's entire industrial sector, it is also harmful to the environment. Unscientific mineral mining is a severe environmental issue, resulting in forest loss, widespread soil erosion, and pollution of air, water, and land (Pal and Mandal, 2017). Mining produces vast amounts of tailings and trash containing heavy metals, posing a serious hazard to water sources, agricultural soils, and food. Increased heavy metal concentrations in soils can induce phytotoxicity, a direct threat to human health, as well as indirect impacts such as pollution of water bodies (Pulford et al., 2002). Unplanned mining activities, as well as a lack of care for land reclamation or mining's environmental effects, have resulted in the formation of vast swaths of industrial wastelands (Ghosh, 1991).

Agroforestry for mined area

Trees can penetrate the stony layer with their roots, causing fissures and allowing surface water to percolate, or holding any quantity of dirt by their roots to protect against erosion and percolation. Ghosh (1991) reported successful species survival after 1 year of reclamation of wastelands of Jharia coalfield, India, by mixed plantation of *Azadirachta indica, Ricinus communis, Phoenix dactylifera, Psidium guajava, Butea frandosa, Leucaena leucocephala*, and *Artocarpus integrifolia*. Species selected for rehabilitation should be N-fixing, fast-growing, well adopted to arid-zone climatic circumstances (i.e., extreme heat and sunlight), and have drought-tolerant root architectural adoption with significant socioeconomic utility. It also helps increase soil microbial activity leading to nutrient mineralization, increased below-ground biodiversity, increased nutrient cycling, and soil matrix stabilization (Datar et al., 2011). Due to the long rotation age of trees to obtain an economic return, combining trees with crops or grasses is a good land-use option for land-use choice for the restoration of mined areas. Seedlings of *Ceiba pentandra* have shown 100% survival when transplanted to ex-tin mining land. Although *Acacia mangium* has thrived in the ex-tin mining land, *Paraserianthes falcataria* does not appear to be adopted to these conditions. Other species such as *Casuarina equisetiolia, Terminalia catappa*, and *Acacia auriculiformis*, also perform well. Datar et al. (2011) reviewed the rehabilitation of post-mined in India and found that four species *Pongamia* sp., *Dalbergia* sp., *Albizia* sp., and *Azadirachta* sp. species have the highest potential for recovering agro-ecosystem function within the context of Indian post-mined landscapes.

Dadhwal et al. (1991) reported that 20 Mg ha^{-1} of mulch was the optimal dose for *Eulaliopsis binata*, resulting in superior results. *Grevillea pteridifolia* and *Eucalyptus camaldulensis* showed excellent survival and growth in 5-year-old plantations in the bauxite mine of Amarkantak. Planting nitrogen-rich leguminous species such as *Leucaena leucocephala* and *Peuraria hirsuta* in mine debris offered fodder, organic manure, mulch, and other benefits. Under geotextiles, *Thysonoleana maximum, Saccharum munja, Pennisetum purpureum, Eulaliopsis binata, Ipomoea carnea,* and *Vitex negundo* performed well (Juyal et al., 2007). Approximately 80% survival and good establishment were obtained when two-thirds of the pit was filled with a mixture of red soil, FYM, and sand after leveling for *Eucalyptus citridora, Dalbergia sissoo, Albizia lebbeck, Casuarina equisetifolia, Acacia auriculaeformis, Leuceana leucocephala*, and *A. nilotica* and in Neyveli (Narayana, 1987). Norem et al. (1982) found that *Acchariss arothroides* and *Nicotiana glauca* were shown prolific growth on the north aspect, while only one shrub, *Dodonea viscosa*, survived on the east aspect. This study suggested the chemical makeup of mine waste material, slope exposure, and species compatibility to the dry climate all have a role in the restoration of mined areas. Successful techniques adopted for the planting of trees in mined areas have been summarized in Table 7.

Industrial wastewater

Industries such as plastics, electronics, electrical, mineral-based dyes, fabrics, chemicals, and other materials, produce industrial wastewater of 50 million liter daily containing a high concentration of heavy metals, chemicals, and dyes (Singh, 2018). With an installed sewage treatment capacity of 21.9 billion liters per day, India produces ~0.5 billion liters of industrial wastewater and 61.7 billion liters of sewage per day (Roy, 2020). Increasingly, industrial effluents and municipal wastes are making their way into freshwater bodies, posing major health and environmental risks (Ranjan, 2021). Many industrial facilities release untreated effluents into water streams due to capacity constraints and poor pricing processes. Oil has been illegally spilled into the Hindon river by industries operating along its banks in the past (Rajput, 2019).

Agroforestry for industrial wastewater

Agroforestry-based wastewater reclamation contributes to the solution to agriculture's growing water scarcity (Ranjan, 2021). Large amounts of industrial wastewater are used as irrigation water. They are regarded as a reliable source of vital nutrients, primarily N, P, K, and organic matter, which are beneficial to soil fertility, plant growth, and production (Libutti et al., 2018). Rasheed et al. (2020) reported an increase of 30% in growth parameters and biomass production, 34% in net CO_2 assimilation rate, and 42% in water use efficiency under wastewater treatment compared to control in *Conocarpus lancifolius* seedlings. Plant species that will be employed for phytoextraction must be able to tolerate heavy metals (HMs). In some plants, HMs are accumulated in the roots, while in others, HMs are transferred to the leaves (Kafil et al., 2019). In response to wastewater irrigation, Zn, Pb, and Cd accumulation increased dramatically in roots, followed by leaves and shoots in *C. lancifolius*. The high translocation of Zn and Cd from the root to the aerial portions of *C. lancifolius* suggests that it has significant phytoextraction capability. *Conocarpus lancifolius* may thus be employed to rehabilitate soils polluted with Zn, Pb, and Cd, because of its improved biomass production, water usage efficiency, metals accumulation, tolerance, and translocation factor (Rasheed et al., 2020). The largest biomass distribution to stem in *A. indica*, twigs in *P. cineraria*, and roots in other species demonstrated the adoption mechanisms by different species when comparing the average contributions of various components in total dry biomass (Singh et al., 2021). The species include *Acacia nilotica*, *Azadirachta indica*, *Cupressus* spp., *Casuarina* spp., *Eucalyptus* spp., *Khaya senegalensis*, *Morus* spp., *Swietenia mahogany*, and *Tamarix* spp. were evaluated successfully under afforestation using untreated and secondary treated wastewater (Singh et al., 2021). Both *Acacia ampliceps* and *Azadirachta indica* demonstrated high biomass increment, high Pb concentrations, and an excellent antioxidative defence mechanism, indicating that they may be utilized for planting in industrial water irrigated soils in Pakistan (Hussain et al., 2021). Wastewater can be an alternative source of water in dryland afforestation if proper species are selected. Several studies highlighted the importance of treated wastewater in urban greening and reducing land degradation along with the usage of freshwater in arid areas. *Eucalyptus camaldulensis*, *S. persica*, *S. oleoides*, and *T. undulata* responded better in terms of survival, adaptation, and growth to wastewater for enhanced productivity in Indian deserts condition (Singh et al., 2021). It was found that plant growth-promoting rhizobacteria can effectively accelerate the phytoremediation process through a variety of mechanisms, including methylation, altering soil pH, encouraging redox processes, and secreting siderophores, bio-surfactants, and a variety of organic acids (Khan et al., 2009). Plant selection, as well as physicochemical soil factors and the research of plant–microbe interactions, could aid in the development of cost-effective remediation solutions.

Waterlogged area

Heavy or prolonged rainfall, over-irrigation, flooding, or high water table leads to waterlogging. In recent years, more intense and unpredictable rainfalls associated with climate change have raised waterlogging incidents worldwide and become one of hazardous abiotic stress (IPCC, 2014). Waterlogging affects various chemical, biological, and physical properties of soil, which in turn affects the ability of soils to support vegetation growth (Kozlowski, 1997). Highly adapted species survive waterlogging periods without any injuries up to a specific period. By contrast, sensitive or less tolerant species can suffer damage within a short period under the oxygen deprivation stage (Kreuzwieser and Rennenberg, 2014). Season, height and duration of flooding, water movement (moving or stagnant), environmental conditions, and various plant-specific characteristics determine the damage's extent (Vreugdenhil et al., 2006). Within the same species, adult trees were more tolerant than younger ones. As an aerobic organism, trees depend on a constant oxygen supply to all living cells of the body and disturbance in metabolism. This leads to disruption in normal functioning at the cellular level based on their tolerance toward the depletion of soil oxygen and damage becomes visible later. Some of the negative impacts of the waterlogging stress in fruit crops include a decrease in net photosynthetic rate, stomatal conductance and root hydraulic conductivity, and hormonal changes (increase in ABA and ethylene), which ultimately result in reduced leaf size, leaf abscission, restriction of vegetative and root growth, etc. (Schaffer et al., 2006). The activity of several metabolic pathways (mineral, carbohydrate, organic acid, protein, lipid metabolism, and hormone relations) reduces under anaerobic circumstances (Kennedy et al., 1991). Waterlogging hampers root growth, root formation, branching, and mycorrhizae formation and causes root decay (Kozlowski and Pallardy, 1997). Ultimately it causes a reduction in flowering, yield, and in severe cases, death of plants through wilting, root necrosis, root rot, etc.

Agroforestry for waterlogged area

Studies have revealed that fast-growing and short-rotation tree-based systems have bio-drainage potential to prevent waterlogging in areas irrigated by canals. The bio-drainage techniques are eco-friendly and economically attractive. Fast-growing tree species such as *Eucalyptus* spp. *Terminalia arjuna, Casuarina glauca, Syzygium cuminii*, and *Pongamia pinnata* are also suitable species for bio-drainage (Uthappa et al., 2015). The block planting of *Eucalyptus tereticornis* at the IGNP site in Rajasthan and Dhob-Bhali in Haryana is very successful in lowering the water table. According to reports, the tree plantations built along the canal drained 14 m of water in just 6 years (Kapoor, 2001). In addition, Ram et al. (2011) observed that the 5-year-old *E. tereticornis* had an average transpiration rate of 30.9 L day^{-1} tree^{-1}, which was 268 mm per year by 240 trees ha^{-1} in comparison to the mean annual rainfall of 212 mm. According to Behera et al. (2015), multifunctional woodlots, agri-silviculture, agi-horticulture, and silvi-pasture are popular strategies for addressing saline and waterlogged situations. Rice, wheat, berseem, mustard, cowpea, pigeon pea, sorghum, turmeric, and annual oat crops were effectively produced beneath *Salix, Eucalyptus, Acacia, Albizia, Terminalia, Prosopis*, and *Populus* tree species in the instance of an agri-silviculture system (Sarvade et al., 2017). Table 8 provides a selection of plants that are appropriate for bio-drainage therapy in salt-affected, waterlogged regions of India.

Chemical degradation

Alteration in soil pH, deficiency or toxicity of nutrients, salinization, alkalinization, and acidification are the processes that lead to the chemical degradation of lands. Both natural and anthropogenic factors contribute to the development of the chemical degradation of land. Saline, sodic and acidic soil are the major form

TABLE 7 Successful techniques adopted for the planting of trees in mined areas in India.

Mine and its location	Species tried	Technique	Survival/result	Source
Singrauli Coal field, Sidhi and Shandol (M.P.), Mirzapur District of U.P.	*Acacia nilotica, Prosopis juliflora*	Planting of seedlings in pits During 1982–1985	50% density cover achieved	Jha (1987)
Dhanpuri coal mine, Shandol District, M.P.	*Eucalyptus* spp., *A. auriculaeformis* and bamboo	60 cm^3 in 2 × 2 m grid pits filled with surface soil of natural sal forest along with 5 kg FYM	70%–94% survival	Prasad and Shukla (1985)
Dolomite mined area, Bilaspur District, Chattisgarh	*Gmelina* spp. *A. auriculaeformis, Eucalyptus* spp. *P. pinnata*	45 cm^3 pits in 2 × 2 m grid filling filled with surface soil of natural sal forest along with 5 kg FYM as above	54%–90% survival,	Prasad and Chadhal (1987)
Rock phosphate and Limestone mined area, Mussoorie hills, Uttarakhand	*Acacia catechu, Dalbergia sissoo, Salix, Pinus roxburghii, Robinia pseudoacacia, Populus* and many local shrubs, grasses, and sedges	Direct sowing, seedling and stump planting, cuttings and rootstocks of local species in contour trenches	60% survival	Soni et al. (1990)
Limestone quarries of Bhilai, Chattisgarh	*Dalbergia sissoo, Pongamia pinnata, A. aurriculiformis, Eucalyptus* spp., *Emblica officinalis, Leucaena leucocephala*	45 cm^3 pits in 3 × 2 m grid filling with surface soil and 2.5 kg FYM per pit	well established	Prasad (1989)
Limestone quarries, Sahastradhara, Mussoorie Hills, Uttarkhand	*Acacia catechu, Bauhinia variegata, Dalbergia sissoo, Salix* spp. *Vitex negundo, Ipomoea carnea, Chrysopogon fulvus, Eulaliopsis binata, Saccharum* spp. etc.	Seedlings planted in contour trenches/pits filled with good soil mixed with mine spoil. Geojute technique to stabilize unstable and degraded mine spoil	well established	Dhyani et al. (1988); Juyal et al. (1998)
Iron ore mine, Dalli Rajhara in Durg District, Chattisgarh	*Dalbergia sissoo, Eucalyptus, Bamboo, Pongamia, Albizia, Emblica officinalis*	45 cm^3 pits in 3 × 2 m grid filling as above with 2.5 kg FYM per pit	Survival 73%–100%	Prasad (1989)
Coal mines of Goa	*Eucalyptus* spp. and *Acacia* spp.	Geotextile laid on laden dump; application of ectomycorrhiza; planting root trainer seedling	Successfully established	Mazumdar and Kulkarni (2016)
Codli and Sonshi coal mines of Goa	*Eucalyptus* spp. and *Acacia* spp.	Application Rhizobium and azotobacter; Pit size = 65 × 65 × 65 m^3; FYM mixed with top soil	Successfully established	Mazumdar and Kulkarni (2016)
OrassoDongor Mine, North Goa	*Anacardium occidentle*	Overburden dumps initially stabilized with fast-growing spp. followed by *Anacardium occidental*	Successfully established	Mazumdar and Kulkarni (2016)
Sanquelim mine, Goa	*Local bamboo, spices and aromatic plants*	–	Successfully established	Mazumdar and Kulkarni (2016)
Open cast Jharia coalfield	*Cassia siamea* and *Albizia lebbek* (2 m × 4 m)	Leveling and mild treatment before planting in pit (60 × 60 × 60 cm) and filled with top soil mixed with farm yard manure and NPK fertilizers.	Soil carbon stock, available N, P, and K increased by 3.5, 5.5, 2.5, and 30-fold along the age gradient of reclaimed mine soil after 16 years soil recovery	Mukhopadhyay and Masto (2022)
Coal field, Ranchi	*Cassia siamea, Dalbergia sissoo, H. ophyllum, A. auriculiformis, L. leucocephala and Acacia mangium*	Backfilling of dumps, planting 2,500 per ha 6-month-old seedlings in pits (pit size: 30 cm × 30 cm × 30 cm)	60%–70% survival and luxuriant growth after 11 years of planting	Ahirwal et al. (2017a)
Jharia Coalmines	*Albizia lebbeck, Dalbergia sissoo and Bambusa arundinacea*	Planting of saplings in 30 cm × 30 cm × 30 cm pit with the addition of topsoil with weathered overburden material in 1:4 ratio		Das and Maiti (2016)
Jharia Coal mines		*Albizia lebbeck* and *Dalbergia sissoo*	accumulation 85% of the natural forest carbon pool after 8 years	Ahirwal et al. (2020)
Coal mines, Ramagundam	*Prosopis juliflora*	Contouring and benching, backfilling, leveling and topsoiling, planting of a seedling in 2000 pits per ha (pit size: 30 cm × 30 cm × 30 cm), and addition of mixture of top soil and spoil in pit in ratio of 1:4	60% of recovery SOC and N stocks as compared to nearby forest sites after 8 years of planting	Ahirwal et al. (2017b)

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of chemical degradation covering 17.4 M ha of land in India. Agroforestry can play an instrumental role in the rehabilitation of these lands.

Saline and sodic soils

Salt-affected soils adversely affect the physiological processes and productivity of plant species across the globe (Singh et al., 2009). These soils modify the soil properties and reduce plant water availability, resulting in the alteration of the structure and function attributes of the exposed plants (Gentili et al., 2018). Salt-affected soils mostly contain Na^+, K^+, Ca^{2+}, and Mg^{2+} cations, CO_3^{2-}, and HCO_3^{-1} (alkali), and Cl^- and SO_4^{2-} (saline) as dominant anions (Zhang et al., 2006). The presence of salts in soils causes alteration of the physiological and biochemical traits of the exposed plant, resulting in low agriculture productivity and deterioration of precious land resources (Parida et al., 2016). Therefore, the reduction in agricultural productivity as a consequence of salinization promotes the interest in growing salt-tolerant tree plantations to increase the sustainability, productivity, and profitability of the salinity-afflicted landscapes (Kumar et al., 2020). Tree species can be characterized as sensitive, moderately tolerant, highly tolerant, or extremely highly tolerant to salt, depending on their level of tolerance (Tomar et al., 2003; Dagar, 2014). Moreover, different salt stress could have a contracting effect on the biomass production and yield of tree species (Banyal et al., 2017). Therefore, agroforestry seems to be the only viable option for obtaining greater ecological and economic benefits for such soils.

Agroforestry for saline and sodic soils

Most of the research findings have indicated that tree plantation improves the soil's physicochemical properties-decrease, the soil pH and EC, and improves the nutrient cycling, organic carbon, and cation exchange capacity of the salt-affected soils (Garg and Jain, 1992; Singh, 1998). In northwest India, salt-tolerant crops such as pearl millet and mustard can be intercropped with *Eucalyptus tereticornis* and *Melia composita* in saline soils (Banyal et al., 2017). The various fruit species, such as Bael (*Aegel marmelos*), Aonla (*Emblica officinalis*), and Karonda (*Carrisa carandas*), along with the salt-tolerant annual crops, were observed to be suitable and economically viable under moderate saline irrigation water conditions (Dagar et al., 2008, 2016). The salt-tolerant multipurpose tree species—such as *P. juliflora*, *A. nilotica*, *Casuarina equisetifolia*, *Tamarixarjuna*, *T. articulata*, and *Pongamia pinnata* have grown in association with various grass species such as, *Leptochloa fusca*, *Chloris gayana, Brachiaria mutica*, and *Sporobolus* spp. in the form of the silvopastoral system have been found highly effective for reclaiming high alkali soil as well as for the fodder production (Dagar, 2014). The block plantation of various tree species, such as *A. nilotica*, *Albizia procera*, *L. leucocephala*, *Azadirachta indica*, and *Eucalyptus hybrid*, was observed to be the best practice for reclaiming the alkali soils. Furthermore, there is tremendous scope for bio-fuels (Energy plantations) in saline conditions under the prevailing scenario of climate change. In areas having abundant saline water, the saline aquaforestry practice consisting of various salt-tolerant fishes reared in the saline water and trees planted on the pond bund has also indicated immense potential in the saline areas (Banyal et al., 2018). In low-lying areas prone to water logging due to the high water table is a major issue, and the biodrainage technique can be designed, which consists of planting waterlogging tolerant species to transpire excess water into the atmosphere and to lower the high water table. Dagar et al. (2016) evaluated the impact of three planting spacings *viz.* 1 × 1, 1 × 2, and 1 × 3 m of *Eucalyptus tereticornis* in waterlogged saline soils. Due to the high transpiration rate of *Eucalyptus*, the water table was lowered by 43.0 cm in 1 × 1 m, 38.5 cm in 1 × 2 m, and 31.5 cm in 1 × 3 m spacing during the 4th year of the plantation than in adjacent fields without plantation. Therefore, the above evidence indicates that agroforestry and tree plantation is the only ecologically and economically viable option to improve the productivity potential of salt-affected soils. The various agroforestry systems developed for saline and sodic soils of India are summarized in Table 9.

Acidic soils

Acidic soil covers ~800 M ha globally (Behera et al., 2011), accounting for half of the world's arable land (Tarin et al., 2021); especially in the humid tropics, soil acidity affects nearly one-third of India's farmed land (Kumar et al., 2012). Acidity affects ~48 M ha of

TABLE 8 Water use and transpiration loss (bio-drainage capacity) of various tree species.

Name of species	Water use	Transpiration loss	Reference
Acacia nilotica	1,248 mm $year^{-1}$	–	Khanzada et al. (1998)
Acacia tortilis		2.63 m mol.m^{-2} s^{-1}	Akram et al. (2008)
Dalbergia sissoo		2.67–3.28 m mol. m^{-2} s^{-1}	Prasath et al. (2014)
Azadirechta indica		2.88 ± 0.2 gm $leaf^{-1}$ h^{-1}	Pagare et al. (2014)
Acacia mangium	–	0.45–4.0 mm day^{-1}	Venkatraman and Ashwath (2016)
Eucalyptus tereticornis	–	0.28–4.0 mm day^{-1}	Venkatraman and Ashwath (2016)
Pongamia pinnata	–	0.1–2.64 mm day^{-1}	Venkatraman and Ashwath (2016)
Eucalyptus grandis	13,184–77,031 kg ha^{-1} day^{-1}	–	Kallarackal (2010)
Punica granatum	1,255–3,671 L $year^{-1}$	–	Bhantana and Lazarovitch (2010)
Prunus armenica	–	1.5–2.37 L day^{-1}	Barradas et al. (2005)
Populus euphratica	–	2.0 mm day^{-1}	Khamzina et al. (2006)

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TABLE 9 Agroforestry systems developed for saline and sodic soils in North-Western zone of India.

Type of degraded land	Agroforestry system	Impact	Reference
Saline and sodic soils	Agri-silviculture system	Strip plantation of *Eucalyptus tereticornis* can reduce high water table (0.75 m in 5 years) and increase crop yield (3–4 times) in the waterlogged saline soils	Singh and Lal (2014)
	Silvipasture system	Grasses: *Leptochloa fusca, Aeluropus* spp., *Eragrostis, Sporobolus, Chloris, Panicum, Bracharia* Trees: *A. lagopoides, S. helvolus, Cynodon dactylon, B. ramosa, Paspalum* sp., *Echinochloa colonum, E. crusgalli, Dichanthium annulatum, Vetiveria zizanioides, & Eragrostis* spp. are grown in association to reclaim sodic soils through fodder production	Dagar (2014)
	Agri-horti system (Fruit trees + arable crops)	Various fruit tree species, such as, *Phoenix dactylifera,Oleaeuropaea,Grewia asiatica*, *Manilkara zapota*, *Psidium guajava*, *Syzygium cumini*, *Ziziphu smauritiana*, *Phyllanthus emblica*, *Carissa carandas, Punica granatum, Aegel marmelos* can be grown in moderately saline soils	Dagar et al. (2008, 2016)
	Sequential Agroforestry System	*Prosopis juliflora* with Kallar grass (*Leptochloa fusca*) can be grown for at least 4–5 years than same land can be put under crop cultivation	Dagar et al. (2001)
	Multipurpose woodlots (Trees)	*A. nilotica, Albizia procera, L. leucocephala, Azadirachta indica, and Eucalyptus hybrid* were identified to be the best suited tree species for sodic soil rehabilitation	Khan and Shukla (2003)
	Agri-silviculture system	Salt-tolerant crops such as Pearl millet and Mustard can be intercropped with *Eucalyptus tereticornis* and *Melia composita* based agri-silviculture systems could be beneficial in terms of economic gains and ecological rehabiliattaion of shallow saline soils of semi-arid regions	Banyal et al. (2018)
	Agri-silviculture system	*Casuarina equisetifolia* and *Dalbergia* sissoo in association with rice and wheat increases system productivity, reduces ph and improve fertility of sodic soil	Parihar and Saxena (2016)
	Agri-horticultural systems	Aonla grown with crops such as Turmeric (*Curcuma domestica*,), ginger (*Zingiber officinale*) and colocassia (*Colocasia esculenta*) for found effective in sodic soils	Das et al. (2011)

India's 142 M ha of fertile land (Mandal, 1997). Soil acidification is caused by natural pedological processes such as carbonic acid influx from the atmosphere and internal acidity generation resulting from organic matter and nutrient cycling (Wong et al., 2004). Soil acidity can also be caused by heavy rainfall combined with nutrient leaching, cation mining from high-yielding crops, acidic soil parent material, and the use of acidifying fertilizers, or a combination of these causes (Xu et al., 2019). In high-rainfall regions, nitrate leaching appears to be the primary source of acidification, followed by the removal of harvested materials (Olego et al., 2021). Acidification in arable soils is primarily caused by crop nutrient extraction and losses of basic cations owing to leaching with downward water flow (Xu et al., 2019), particularly of Ca (Litvinovich et al., 2021).

Agroforestry for acidic soil

Trees play a great role in the agroforestry system. Tree-based systems reduce nitrate leaching more efficiently than tree-less systems, and deep-rooted trees absorb leached base cation from deep layers and are pumped back to the top layer *via* litterfall through nutrient pumping. In general, tree-based systems keep the SOM content higher than tree-less systems (Muchane et al., 2020). The key soil acidity management component in tropical habitats is the agroforestry method of management (Fageria and Nascente, 2014). Muchane et al. (2020) reviewed the acidity alleviation potential of agroforestry systems and concluded that overall, agroforestry practices elevated soil pH compared to monoculture, with minor differences depending on soil type. The incorporation of plant materials into acid soils or litterfall has resulted in higher soil pH, decreased Al saturation, and enhanced plant growth conditions in several laboratory trials. These plant materials also provide base cations such as Ca, Mg, and K (Wong et al., 2004). *Gliricidia sepium* had the greatest effect on improving soil pH and lowering monomeric Al content at the 10th week of incubation by its high base cation content. Application of 15 Mg ha^{-1} *Gliricidia sepium* biomass suppresses monomeric Al to the same amount as 90 Mg ha^{-1} *Melastoma* biomass or 15 Mg ha^{-1} *Peronema* biomass, according to a prior pot experiment (Hairiah et al., 1996). Alkalinity resulting from the deposition of leached base cations in a deep soil and mineral weathering might be exploited by deep-rooted perennial plant species in the agroforestry system (Wong et al., 2004). *Senna siamea* has been proven to recycle calcium from subsoils and improve pH in the top soil considerably (Vanlauwe et al., 2005). Trees that produce high-calcium litter are frequently linked to soils with higher exchangeable Ca, percent base saturation, and pH and are also associated with greater abundance and activity of soil organisms (Muchane et al., 2020). In charcoal-making areas of *Acacia decurrens*-based agroforestry landscape in Ethiopia, soil pH improved by one unit, and SOC increased by 10%, which was comparable to applying lime 4–5 t^{-1} (Amare et al., 2022). Incorporation of pruning's of immature tree branches of *Calliandra calothyrsus, Cassia siamea, Flemingia congesta, Grevillea robusta, Gliricidia sepium, Leucaena diversifolia*, and *Leucaena leucocephala* resulted in a rise in soil pH and a reduction in exchangeable Al concentration due to high base cation content of the pruning 0.94–2.25 mol kg^{-1} (Wong et al., 2000). The liming impact of adding plant material or perennial components of agroforestry depends on is proportional to the total base cation charge (Wong et al., 2004). Trees with higher amounts of P or base cations such as *Gmelina arborea* rich in Ca and Mg alleviated soil P and pH (Wong et al., 2004).

Biological degradation

Degradation of soil biological quality is often associated with all forms of land degradation and does not occur exclusively as biological degradation of soil. Land degradation of any form negatively affects microbial diversity and impacts the sustainability of the ecosystem (Araujo et al., 2014). Biological degradation involves the loss of SOM or soil organic C, which is a prime component for the survival and proliferation of soil microbes. This subsequent loss of SOM/SOC triggers various negative impacts on the soil's biological properties, which in turn harms the capacity of soil to perform several ecosystem functions and services. Loss of SOC often triggers microbial biodiversity loss (Singh, 2015), and it is expected that the greater the soil microbial diversity greater the chance for the ecosystem to establish functional equilibrium (Seneviratne, 2012). Soil microorganisms are the key to regulating the C cycle, as they are directly involved in the mineralization and immobilization of C from organic matter. The microbial diversity in the soil is thus important to regulate the fate of SOC and maintain soil health and productivity. It is estimated that enhancing soil biodiversity could result in 2.3 BT of additional crop production per year in the United States, with a monetary value of US$ 1.4 trillion (IUCN, 2019). The relationship between soil biodiversity and soil erosion losses is multifaceted and non-unidirectional (Orgiazzi and Panagos, 2018). Soil diversity may impact the problem of soil erosion in many ways. When considering macrofauna such as earthworms which are more abundant in less disturbed soils with high organic matter content, their abundance will harm soil erodibility. Certain studies have shown that the presence of earthworms can bring about a 50% decline in soil erosion rates (Blouin et al., 2013), which is mainly attributed to the increased soil porosity, higher infiltration rates, etc. On the contrary, mammals inhabiting the soil such as moles and rats can lead to the weakening of soil structure by burrowing activities which enhances soil erosion (Shuster et al., 2002). According to global research by Guerra et al. (2020), soil erosion affects not only soil conditions' sensitivity but also its biodiversity, with 6.4% of these susceptible locations for soil macrofauna and 7.6% for soil fungus also occurring in areas with high soil biodiversity. Wu et al. (2021) studied the impact of N-enrichment and vegetation loss on soil microbial diversity. Both the degradation process had a detrimental effect on microbial diversity. However, the common soil fungi were less affected by N-enrichment compared to other microbial groups, which can give a clue about the resilience of the microbial groups toward degradation.

Fungi, particularly, have a major role in soil conservation through their physical and biochemical association with plants. Symbiotic association of plant roots with fungal hyphae, particularly arbuscular mycorrhizal fungi (AMF), can have a positive impact on soil structure and hence helps in arresting soil erosion. Plant root architecture and the soil moisture regime in the rhizosphere are greatly influenced by the association of AMF with plant roots. AMF imparts efficient water utilization, stronger wetting–drying cycles, stronger aggregates (Roy et al., 2021), and a reduction in soil loss (Mardhiah et al., 2016). The AMF inoculation helps in river bank slope stabilization and acts as a measure of soil conservation (Kimura and Scotti, 2016) due to the presence of Glomalin, a stable protein in AMF (Treseder and Allen, 2000). Glomalin has revolutionized the importance of AMF in soil conservation and is likely to play a crucial role while discussing soil biodiversity and land degradation.

Agroforestry for biologically degraded lands

Global food security and environmental sustainability depend on maintaining and improving soil fertility. Intercropping and mixed arable-livestock systems are two examples of ecologically appropriate agroforestry systems that can improve the sustainability of agricultural output. A helpful alternative to chemical fertilizers for increasing soil fertility is agroforestry. SOM restoration is more successful with alternative land-use systems including agro-horticulture, agro-pastoral, and agro-silvipasture. Choudhary and Rijhwani (2020) reported that the higher microbial diversity rates in agroforestry systems and the agro-silvopastoral system as compared to monoculture reported in Rajasthan as integrating trees provide favorable conditions for soil microflora to flourish. Yadav et al. (2011) reported that tree-based traditional agroforestry systems involving *Acacia leucophloea, Dalbergia Sissoo*, and *Prosopis cineraria* improved the microbial biomass of carbon by 40%–72%, microbial biomass of N by 38%–82% and microbial biomass of P by 38%–85% compared to open fallow in a semi-arid region of Rajasthan, India. Ghosh et al. (2019) observed that an anonla-based horti-pasture system improved the biological health of degraded lands in the Bundelkhand region of Uttar Pradesh, India. They reported that an anonla-based horti-pasture system along with staggered contour trenches and continuous contour trenches improved the SOC, bacterial and fungal density, soil enzyme activity, and treated soil quality index by 51% and 31%, 20% and 95%, 42% and 89%, and 154% and 184%, respectively, in surface soil over control. With the right species, soil fertility may also be restored in mobile farming zones. *Sesbania rostrata and S. cannabina* produce 307 and 209 kg N ha^{-1} of biological N_2 fixation, respectively, when stem cuttings are planted, and irrigation is used to restore fertility (Pandey, 2007). The species mix should be planned for nutrient release that helps crops, even if trees are not completely harvested. *Alnus nepalensis, Albizzia lebbek, Boehmeria rugulosa, Dalbergia sissoo, Ficus glomerata*, and *F. roxburghii* were the six MPTS with the highest rates of nutrient release when established on an abandoned land at 1,200 m altitude in Central Himalaya. Thus, even though the only source of nutrients for crops in mixed agroforestry is leaf litter, *Kharif* crops (crops grown during the rainy season) contain high levels of nutrients. A variety of multifunctional trees contribute to steady nutrient cycling and a wide range of goods (Kerkhoff, 2006). Changes to aspects like the delivery of regulated ecosystem services are seldom taken into consideration in field and crop management, in part because there is a lack of thorough quantification of how trees alter biophysical field features. This is especially true for temperate climate arable systems. As a result, the effect of rows of trees of different sizes on the dominant soil properties in an agroforestry system for arable land was evaluated. In the area of trees in field margins, significantly increased SOC and soil nutrient concentrations of N, P, K, Mg, and Na were reported. This is likely due to the entry of tree litter and nutrient-enriched fall water (for K and Na). The potential of middle-aged to mature tree rows to boost SOC stocks and nutrient availability for the agricultural crop in an agroforestry system is highlighted by these results (Pardon et al., 2017). Large plant residue deposits on the soil caused by agroforestry systems result in high SOM content, greater soil biodiversity, and improved soil conservation. The cacao agroforestry systems used for cacao cultivation in the southern Bahia area of Brazil have positive impacts on the faunal populations that live in the soil and litter, and such systems of cacao cultivation may be thought of as a strategy for soil fauna conservation. A higher quantity and variety of soil fauna were produced as a result of the formation of a litter layer (da Silva Moco et al., 2009).

A notion known as “planetary health” refers to how human actions alter the structure and function of the environment with repercussions for human health. Agroforestry, which involves managing trees alongside crops and animals, affects biodiversity, hydrology, and biogeochemistry. But aside from the added nutritional value of eating more fruit, agroforestry’s effects on human health are rarely discussed. The research implies that agroforestry is likely to address a variety of urgent health conditions, notwithstanding some elevated risks of infectious diseases (Rosenstock et al., 2019). Agroforestry contributes to a reduction in soil-borne diseases. Such research was carried out in Brazil’s Atlantic rainforest. Fusarium wilt, often known as Panama wilt, is one of the most detrimental banana diseases and is brought on by the soil-borne fungus *Fusarium oxysporum f.* sp. *cubense* (Foc). Foc is pervasive in practically all banana-growing regions and is resistant to chemical or biological management. The development of disease-suppressiveness in soils may be able to control fusarium wilt, but little is understood about how soils might become more disease-suppressive and how crop management can affect this. Banana variety (cv.) In Pedra Dourada, Brazil, where Foc race 1 is found in the soil, maca, a cultivar that is extremely vulnerable to Foc race 1, was produced on a farm run as an agroforestry system. The findings of this study show that a good plant arrangement, in which cv. Maca is grown in mixed stands with other banana types, which might aid in the promotion of Fusarium wilt suppression in soils with positive abiotic qualities (Deltour et al., 2017). Contrary to monocultures, the integration of trees into agroforestry systems can boost the sustainability of the system. The altered structure and functions of the soil microbial community as a result of the system complexity increase are expected to have an impact on soil-N cycling. In both soil types, the ratio of soil fungus to bacteria was higher in the tree row than in the crop or grass rows of monoculture farmland and open grassland, presumably because more tree wastes were added and there was no tillage in the Phaeozem (cropland) soil. It has been demonstrated that the number of soil bacteria, fungi, and soil-N-cycling genes, particularly those involved in ammonium oxidation, can change in temperate regions when monoculture cropland and open grassland are converted to agroforestry systems (Beule et al., 2019).

According to Roy et al. (2009), the farm stage is a significant contribution to the effect categories of global warming, eutrophication, and toxicity. Agricultural production is often a hotspot in the life cycle of food goods (Salomone, 2003; Humbert et al., 2009; Pleanjai and Gheewala, 2009; Cappelletti et al., 2010). Hence there is a need for a paradigm shift from a monoculture to an agro forestry system to promote sustainable agricultural practices. With contributions of 3.67E ± 01 kg CO_2, 4.31E-02 kg SO_2, and 2.25E-05 kg PO_4-eq, respectively, to global warming, acidification, and eutrophication, cocoa–coconut agroforestry had the least influence on these global impact categories. In addition, cocoa–coconut agroforestry had the highest SOC and SOM, fostering the development and activity of helpful soil microbes (*Pseudomonas* sp. and *Trichoderma* sp.). In addition, the cocoa–coconut agroforestry total land equivalent ratio got the greatest value, 1.36, indicating a higher production advantage. As a result, promoting cocoa–coconut agroforestry might be a smart move to ensure the environmental sustainability of cocoa farming (Utomo et al., 2015). In forest ecosystems, soil microorganisms, particularly bacteria, are common and essential to processes like the biogeochemical cycle and nitrogen transformation for plant development. The main factors influencing these bacterial community patterns were found to be soil pH, accessible P, and dissolved organic nitrogen. Establishing rubber-based agroforestry systems is a viable management strategy for reducing the negative impacts of rubber monoculture on bacterial biodiversity, including severe acidification and nutrient depletion. This is especially true for systems in mature stands (Liu et al., 2019).

National Agroforestry Policy 2014

The Indian government has formulated National Agroforestry Policy, 2014, to converge and establish synergy between various elements of agroforestry scattered in various existing missions, programs, and schemes of the Government. The policy aim is to promote agroforestry programs and encourage farmers to practice agroforestry to meet the ever-increasing demand for timber, and non-timber forest produces, increase forest/tree cover, conserve the environment, and mitigate climate change. The policy was targeted to address the various constraints and challenges, such as the provision of quality plating material, relaxation of legal provisions, financing and marketing of agroforestry produce, and improving agroforestry research and extension in the country. The major goal of the policy is to improve productivity, increase employment, provide livelihood opportunities, and generate income for smallholder farmers through agroforestry interventions. The proper implementation of this policy could fulfill the target of land degradation neutrality through planting trees in the degraded lands. Subsequently, the national agroforestry mission was established to fulfill the objective envisaged in the national agroforestry policy (Chavan et al., 2015).

Future strategies and action plans for agroforestry

Agroforestry has demonstrated immense potential in reclaiming the degraded lands of India. The government of India has also initiated various programs and formulated several policies for supporting agroforestry in the country. Therefore, the following strategies and action plans should be considered for large-scale rehabilitation of degraded lands through agroforestry in the country:

- Development of need-based agroforestry technologies through multi-locational trials in various agro-ecological zones to upscale the best agroforestry practices and models in the different regions of the country;
- Cloning and mass multiplication of superior germplasm of tree species for developing the quality planting material suitable for the degraded soils;
- Development of Hi-tech nurseries for the production of quality planting materials for potential species in different agro-climatic zones of the country;
- Creation of the center for the excellence of each species in different regions by involving the nursery growers and state governments;
- Developing cultivation and management practices of high-value tree species for degraded soil conditions;
- Identifying and developing climate-resilient agroforestry systems for climate change mitigation and adaptation in degraded lands;
- Enhancing the abiotic stress tolerance of tree spp. through selection, improvement, and breeding approaches;
- Develop appropriate metrics and indicators to measure the intangible advantages and environmental externalities of ecosystem payment services provided by agroforestry;
- Simplifying the regulations about harvesting and selling of tree produce for exploring the full potential of agroforestry;
- Development of agroforestry-based business models by involving local farmers, research institutions, and private industries;
- Adopting mechanization in agroforestry right from plating to harvesting to reduce dependency on manual labor;
- Post-harvest and value addition in trees for getting the maximum benefits;
- Provision of easy and subsidized access to quality plating material to the farmers;
- Removal of legal hurdles hindering the planting, harvesting, and transporting of tree produce;
- Initiation of insurance and credit and subsidy scheme and low-interest financing mechanisms to farmers for adopting agroforestry practices;
- Comprehensive awareness-raising and capacity-building initiatives to promote agroforestry at all levels, including those of farmers, extension agents, village-level organizations, and cooperative societies for tree producers; and
- Creation of institutional mechanisms for coordinating and bringing together the ministries' and schemes' efforts to pursue agroforestry thematically.

In addition, Parthiban et al. (2021) have suggested several research, technological and policy interventions, such as an organized supply chain, buyback agreement with MSP, analysis, and sensitization of price, creation of supportive price mechanism, insurance and credit facilities, tax exemption, processing technology facilities, promotion of mechanization, efficient post-harvest management, value addition, development of high-yielding varieties, and clonal planting material, reducing the rotation, adoption of precision silviculture and profitable tree crop model, that could be helpful in dissemination and promotion of agroforestry models in India. Moreover, considering the success and constraints of past and present agroforestry practices, there is an urgent need to focus on developing high-value tree species-based agroforestry practices with a focus on productivity, profitability, and sustainability. The tree species, such as *Santalum album*, *Tectona grandis, Pterocarpus santalinus*, *Aquilaria, Swietenia Mahagoni*, and *Melia dubia* are considered highly valuable and preferred by the farmers. These species could be easily integrated with different agroforestry practices, such as agri-silviculture, silvi-pastoral, agri-horti-silviculture, and block plantations and can greatly increase farm income, restore degraded lands, and provide resilience against climate change.

Constraints and challenges for agroforestry in degraded lands

In India, significant progress has been made in agroforestry research and development. The different agroforestry models and practices have been identified and developed for rehabilitating degraded lands, resulting in substantial improvement in productivity and profitability from such lands. Despite the huge potential of agroforestry in terms of reclaiming problematic soils, enhancing land productivity, generating additional income, and mitigating climate change in the degraded lands. Several constraints and challenges at the regional and national levels are hindering the promotion and large-scale adoption of agroforestry practices. The constraints, such as lack of quality planting material, poor scientific management inputs, several legal barriers on cultivation, harvesting, transportation and selling, non-payment for ecosystems and environment services, and long gestation period of trees are the main bottlenecks hampering the large-scale cultivation of trees in agroforestry. Furthermore, the lack of suitable silviculture and cultivation techniques, poor extension strategy and training facility, non-implementation of policies, non-availability of organized markets, a monopoly in price fixation, low price, and non-availability of tree loan and insurance schemes are further hindering the cultivation of trees (Cooper and Denning, 2000). In addition, Parthiban et al. (2021) highlighted several challenges, such as an unorganized supply chain, weak buy-back system, insufficient market intelligence, policy issues on taxes, lack of alternate processing technology, poor mechanization, under-utilization of residues, inferior genetic resources of trees, low productive species, and lack of profitable trees-crop model, which were responsible for the poor dissemination of agroforestry in India. Moreover, most of the agroforestry practices developed in India were primarily focused on obtaining the environmental and reclamation benefits and secondary getting the economic benefits, which were one of the main reasons for the low adoption of agroforestry by the farmers. These issues get further aggravated while practicing agroforestry in degraded lands. Therefore, there is an urgent need to develop strategies and devise action plans for a greater success of agroforestry in India and particularly in degraded lands.

Conclusion

Restoration of degraded land is an important challenge in the Indian subcontinent. Agroforestry has demonstrated great potential in the sustainable rehabilitation of degraded lands. The various kinds of agroforestry practices, such as agri-silviculture, silvi-pastroral, and agri-horticulture have shown strong potential to provide ecological and economic benefits from these lands. Many potential species for agroforestry exist in India; the only requirement is harnessing their potential and bringing them into agroforestry-based business models. Moreover, the widespread cultivation and adoption of high-value trees by farmers can lead to a tremendous impact in terms of an increase in farm income. More studies are required to develop agroforestry practices that can be widely accepted by farmers and stakeholders. Understanding fundamental processes and implementing technology well would be crucial for successfully managing and repairing degraded lands through agroforestry. Moreover, effective agroforestry-based technological implementation is urgently needed to obtain the desired result to fulfill the "Bonn Challenge" goal of rehabilitating 26 M ha of degraded land by 2030. Therefore, to meet the UN's land degradation neutrality target, it is necessary to develop appropriate agroforestry practices, policies, and action plans for the greater promotion and adoption of agroforestry in India.

Author contributions

DJ, RKa, RKu, VP, AV, MS, SC, VK, SD, AU, TR, VS, MM, DK, PK, DD, GS, AS, AN, NJ, EJ, and SK together designed the scope of the manuscript, wrote individual chapters, and prepared the figures. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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