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Review

Agroforestry Systems for Soil Health Improvement and Maintenance

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Abstract: Agroforestry integrates woody perennials with arable crops, livestock, or fodder in the same piece of land, promoting the more efficient utilization of resources as compared to monocropping via the structural and functional diversification of components. This integration of trees provides various soil-related ecological services such as fertility enhancements and improvements in soil physical, biological, and chemical properties, along with food, wood, and fodder. By providing a particular habitat, refugia for epigenic organisms, microclimate heterogeneity, buffering action, soil moisture, and humidity, agroforestry can enhance biodiversity more than monocropping. Various studies confirmed the internal restoration potential of agroforestry. Agroforestry reduces runoff, intercepts rainfall, and binds soil particles together, helping in erosion control. This trade-off between various non-cash ecological services and crop production is not a serious constraint in the integration of trees on the farmland and also provides other important co-benefits for practitioners. Tree-based systems increase livelihoods, yields, and resilience in agriculture, thereby ensuring nutrition and food security. Agroforestry can be a cost-effective and climate-smart farming practice, which will help to cope with the climate-related extremities of dryland areas cultivated by smallholders through diversifying food, improving and protecting soil, and reducing wind erosion. This review highlighted the role of agroforestry in soil improvements, microclimate amelioration, and improvements in productivity through agroforestry, particularly in semi-arid and degraded areas under careful consideration of management practices.

Keywords: agroforestry; soil health; land degradation; microclimate; soil fertility

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1. Introduction

A dynamic and living resource, the soil is crucial for maintaining global biogeochemical cycling, ecosystem health, and sustainable food production. However, a lot of farmland soils are severely degraded [1]. Although productive, annual row cropping practices damage surface and ground waters, degrade soils, raise greenhouse gas emissions, and speed up the loss of biodiversity [2]. Particularly concerning is the deterioration in soil health, which potentially has an impact on agricultural production over time [2]. According to the United States Department of Agriculture's National Resources Conservation Service [3], soil health is the persistent capability of the soil to function as an extremely important ecosystem that supports vegetation, animals, and human being." The ability of soils to enhance and sustain agricultural output, absorb carbon, reduce nutrient leaching, and conserve biodiversity adds to soil health, which also incorporates the functioning of ecosystem services provided by soils. Roughly 73% of rangelands in drylands, 47% of marginal rainfed arable lands, and sizeable portions of irrigated arable lands are now being degraded [4]. According to the FAO [5], 25% of the world's soil has severely deteriorated and 50% is moderately damaged [6] as a result of a variety of anthropogenic activities during the past few decades. Breaks in the natural fallow cycle due to population growth and the resulting reductions in per capita available land are responsible for the degradation of soil fertility; 60% of SOC was lost when land was converted from natural land to farmland in temperate climates, and 75% or more was lost in tropical regions [7]. Soil organic carbon has been depleted as a result of heavy tillage, intensive cropping, and insufficient C inputs [8]. It is acknowledged that substantial soil erosion and poor soil fertility are the primary biophysical causes of food insecurity [9]. Therefore, one of the main objectives in the development of sustainable farming techniques is to improve soil health [2]. There is a need to protect and enhance soil health, as soil is the most important resource for future generations [10]. It is the responsibility of the entire globe to maintain food and nutrition security for upcoming generations by increasing agricultural land production while significantly reducing the environmental impact [11].

To minimize soil erosion and increase farmland production, conservation farming techniques such as residue return, zero tillage, minimum tillage, cover cropping, and crop rotation [1] have been developed. These methods are intended to enhance soil, water, and agro-ecosystems, primarily by minimizing soil disturbance, increasing the amount of plant residue on the surface, and boosting biodiversity [1]. Agroforestry is an agricultural technique that focuses on diversifying various agro-ecosystem production components such as woody perennials, palms, crops, forages, or animals [12]. Agroforestry is considered practical agro-ecology due to its ecological approaches and principles on which its design and management are based; it is subject to various interactions between trees and crops and has been identified as a potential intensification pathway to make agriculture more sustainable [13]. Based on the combination of various production components, agroforestry systems are grouped into silvopastoral (trees + pasture), silvi-agriculture (trees + agricultural crops, e.g., alley cropping, windbreaks, shelterbelts, etc.), and agro-silvopastoral systems (trees + crops + livestock) [2,12]. Perennial systems performs better than annual croplands in terms of soil health due to higher belowground C inputs and less soil disturbance [13]. Since agroforestry mimics the composition and operations of natural woody perennial ecosystems, it has the potential for agricultural sustainability. Additionally, by serving as a significant supply of soil organic matter, the agroforestry approach can affect the physical, chemical, and biological soil qualities and promote plant development [1]. By stabilizing soils, encouraging aggregate formation, storing carbon in soils, enhancing the availability of nutrients, and retaining and fostering a healthy soil biota, agroforestry can restore soil health. Agroforestry has been recommended as a approach to achieve carbon neutrality; however, there are many obstacles to overcome [14]. Crops diversification in agroforestry systems promotes higher crop, timber, or fodder yields than monocropping of the same crops. However, compared to tree-based systems for biomass or lumber production, the advantages of agroforestry for food systems for soil health are less widely researched [2]. The published studies have focused only on certain sets of soil quality indicators. Thus, in this review, we group all soil quality indicators into a single review paper and present an overview of soil health improvement through agroforestry. Although soil health is a broad term, an improvement in soil quality parameters such as the various chemical, biological, and physical properties of the soil is considered a proxy for soil improvement in this paper.

2. Soil Improvements and Microclimate Amelioration through Agroforestry

The influence of agroforestry on soil quality through changes in ecosystem functions and services caused by direct and indirect effects of trees varies depending on the crop type, climate, and geography. Trees play an important role in the cycling of nutrients by recapturing and pumping back leached nutrients via deep roots, which work as a 'safety net' against nutrient losses from the nutrient cycle (Figure 1). Trees in tree-based systems also capture nutrients present in the atmosphere and help in dry deposition [15]. Agroforestry provides a promising opportunity to store and capture carbon in the soil that is lost due to the intensification of agriculture and the use of heavy tillage and fertilizers [16]. Agroforestry promotes more effective resource usage than monocropping due to the structural and functional diversity of the components acquired in a mixed cropping canopy [17]. The integration of trees on farms enhances the field capacity (FC), organic matter (OM) [16], available potassium, available phosphorus, soil carbon stocks [18], and lower bulk density (BD) [17], which retain water by increasing the water holding capacity (WHC) and release the water to plants gradually like a sponge [15]. The addition of OM plays an important role in soil aggregation and in reducing the bulk soil density. This reduced BD of the soil helps with air circulation, the distribution of water in the rhizosphere, and improving the groundwater recharge and nutrient quality of the soil in arid and semi-arid areas [18]. The accumulation of litter through the shedding of leaves and twigs is the main source of nutrients and organic carbon (OC) in agroforestry systems. The soil organic carbon (SOC) influences the efficiency of nutrient usage in agriculture directly and indirectly. The nutrient use efficiency will be enhanced due to the increased absorption and availability of soil with high OM and an active deep root system [19]. Additionally, the increased microbial diversity due to OM addition [20] probably provides mycorrhizae, releasing P and making it accessible to crops [21].

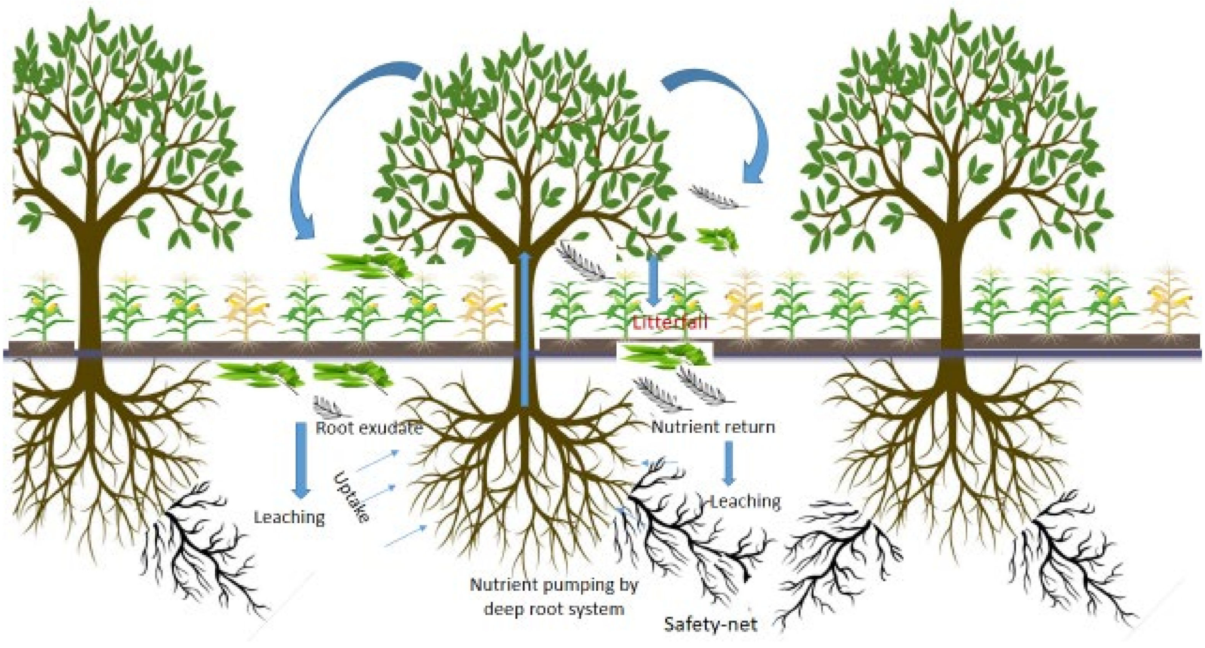

Figure 1. Nutrient pumping and cycling in an agroforestry system via 'safety net' formation.

The nitrogen fixing in the trees enhances the amounts of soil and N cycling through the decomposed leaf litter and improves the long-term soil N through OM additions. Additionally, closed and more efficient N cycling results from the nutrient pumping of N from deep soils to the root zone of maize via deep tree roots [22]. The introduction of leguminous as well as non-leguminous species such as durian and rambutan in cocoa-based agroforestry positively influences the nutrient content in the soil [23]. Tsufac et al. [24] examined farmers' perceptions toward agroforestry in the southwest region of Cameroon and found that about 53% of farmers considered the agro-silvopastoral system to be the most successful in increasing soil fertility, with 57% of farmers believing that the agro-silvopastoral system provided the highest degree of soil fertility. Nath et al. [25] have also reported higher available P and K in agroforestry systems than via monocropping. A study by Riyadh et al. [26] in Bangladesh reported 3.37–9.25% reductions in soil temperature, 10–20% increases in soil moisture, and 9–19% increases in total nitrogen in the soils in different crops associated with jackfruit-based agroforestry than in open seasonal crop fields. Thus, it is proposed that the use of jackfruit-based agroforestry systems might promote soil fertility by improving the physical and chemical soil qualities. Both guava and poplar-based agroforestry systems showed increased SOC as compared to monocropping [27]. The integration of trees on farmlands may improve physicochemical soil properties [28] (See Figure 2 for more information). The better cycling of basic cations in the agroforestry system might assist in the amelioration of soil acidity [26].

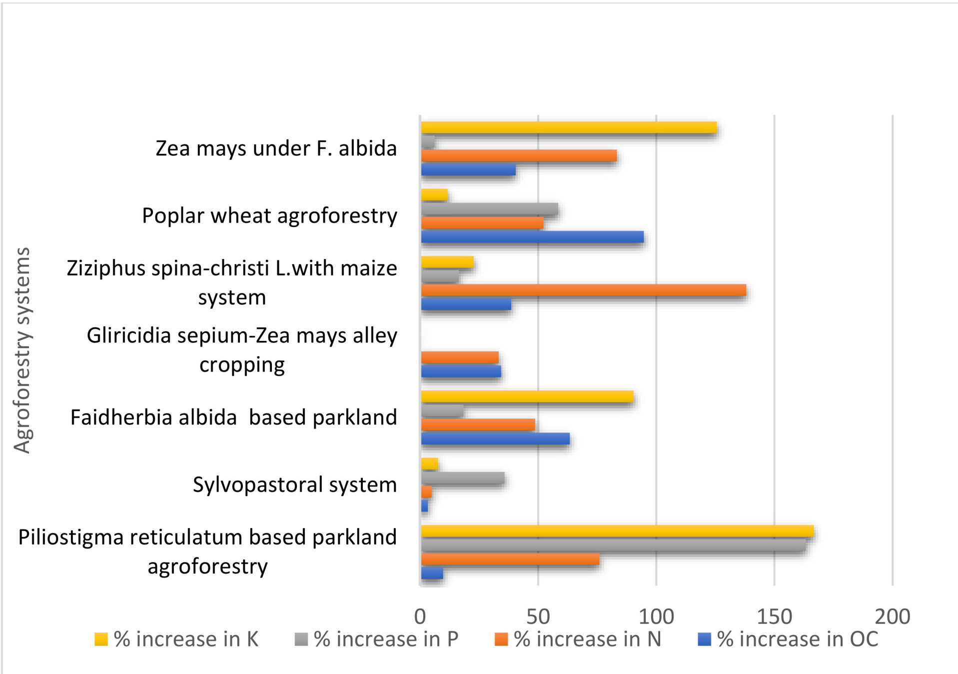

Figure 2. Percentage increases in soil N, P, K, and organic carbon as compared to controls in various studies (data sourced from [22,29–34].

Surki et al. [18] found the highest carbon stocks in agroforestry plots at 0.5 m from almond rows, which were almost twice the carbon stocks found in monocropping systems of clover, wheat, and barley. The highest FC (28%) and SOC (1.82%) rates were observed in the agroforestry systems near the trees. Mohamed [35] cited that in Sudan, *Acacia senegal* + sorghum inter-cropping systems improved crop yields and certain soil properties. The wheat–poplar intercropping system incorporates higher levels of available soil K, N, and P than sole wheat cropping, largely through the fixation of atmospheric N and the mineralization of organic matter [36]. Salve and Bhardwaj [37] compared the physicochemical soil properties of different agroforestry systems in a temperate region of Himachal Pradesh, India, and reported that the agri-horticulture, agri-silviculture, and agri-hortisilviculture systems can enhance the carbon density and physical soil properties in cold deserts. Shoga'a'Aldeen et al. [32] studied the influence of various agroforestry systems on the fertility of soil and reported that mixed trees with coffee plants and *Cordia africana* with coffee plants accounted for higher N (0.17–0.26%) and soil P, K, SOC, and OM concentrations as compared to *Ziziphus spina-christi* with maize and maize sole cropping. Gusli et al. [38] demonstrated that switching from cocoa monoculture to various kinds of agroforestry benefited farmers by buffering the temperature and soil moisture and enhancing the soil structure moderately, which helps the plants to tolerate the dry season.

Agroforestry leads to higher soil C-sequestration rates; moisture contents; and levels of available soil K, N, and P, the residues of which are available for subsequent crops, allowing more sustainable farming in the upcoming seasons and reducing the use of chemical fertilizers [18]. Narendra [39] demonstrated that N-fixing green manure trees had the potential to improve the soil properties (organic matter, total N, CEC, permeability, infiltration, water content, and BD) of pumice-mined land areas on Lombok Island, which is important for teak growth. Yadav et al. [40] studied different trees (*Prosopis cineraria*, *Dalbergia sissoo*, and *Acacia leucophloea*) in farms in the semi-arid areas of Rajasthan and estimated that the available contents of N, P, and soil microbial biomass of C were in the ranges of 32.1–42.4, 11.6–15.6, and 262–320, μg g^{-1} in soil, respectively. Among the different agroforestry systems, higher C, N, and P levels were observed for *Prosopis cineraria* based systems. A decrease in soil respiration and an increase in SOC were reported when avocado trees were integrated with a shaded coffee system in Mexico [41]. Eddy and Yang [2] reported higher total nitrogen stock and SOC levels up to 1 m in 24-year-old *Castanea mollisima*–*Asima trilobala* agroforestry than in a zero tillage corn–soybean rotation system in the USA. Mesfin and Haileselassie [9] reported increased SOC, total N, available phosphorus, exchangeable potassium, and SOC stock levels by 11.9–91.5%, 22.2–125.0%, 31–71%, 32–151.6%, and 15.2–90.9%, respectively, in the soil under the tree canopy compared to outside the canopy. In croplands, the presence of a few scattered trees greatly increases the nutrient status of the soil and decreases the requirement for an additional input of fertilizer. In terms of managing soil fertility, *Faidherbia albida* has the most potential as compared to *A. sieberiana*, *Balanites aegyptica*, *Cordia africana*, *Croton macrostachyus*, and *Ziziphus spina-christi*. In Ethiopian farms, *Faidherbia albida* reduces allelopathy and shadowing effects by dropping its leaves during the wet season and encouraging crop production under its canopy [9]. Planting tree species on croplands is an effective approach to enhance the nutrient status of the soil and lower the requirement for external fertilizer inputs. Near the tree row, the maximum soil nitrogen (365.2 kg ha^{-1}), phosphorus (19.7 kg ha^{-1}), and potassium (357.3 kg ha^{-1}) values were discovered at a distance of 2 m in Haryana [42]. De'Stefano and Jacobson [43] found that the switch from traditional agriculture to agroforestry increased the SOC stock levels by 26% at 0–15 cm, 40% at 0–30 cm, and 34% at 0–100 cm soil depths. In Haryana, India, under a poplar windbreak, the P and K availability levels were found to be greater than in the solitary crop area (control) [42]. At soil depths of 10–20 cm, the SOC levels in agroforestry buffers, grass buffers, and grass waterway regions were 3, 8, and 7% higher than those in the corn–soya row crop, respectively, 23 years after their implementation in the USA [8]. The soil N levels increased by 118.75% [37] to 237.5% [39], soil P by 119.75% [37] to 158.12% [33], and soil K by 111.03% [33] to 125.2% [37] in agroforestry as compared to control systems (monocrop or open cropping areas).

Shade trees alter the microenvironment beneath coffee plant by lowering the incoming radiation, reducing the maximum temperatures, decreasing the temperature amplitude, and increasing the minimum temperatures. Shade trees in coffee gardens shelter coffee plants from high temperatures and radiation while also reducing seasonal variations in the coffee leaf area. Sarmiento-Soler et al. [44] found that a coffee–*C. africana* system minimized incoming radiation and provided greater buffering against extremes, resulting in a smaller daily temperature amplitude than in open coffee plants. The wind speed reduction was greatest (5 m) adjacent to the willow strips (50% in alley cropping and 58%

in the windbreak systems), moderate at 20 m, and negligible at 50 m from the windbreak system. In comparison to the control plots, a considerable increase in the mid-day air temperature of about 1 °C, a 44% increase in fodder yield, and increased soil moisture were seen close to the willow strips in a windbreak system in Canada [45]. Soil and microclimate improvements due to the introduction of trees in farms are depicted in Table 1.

Table 1. Improvements in physical and chemical soil properties through agroforestry.

Region	Agroforestry System	Changes in Soil Metrices	Open/Control	Author
Uttarakhand, India	Wheat–poplar alley cropping	pH (7.9), EC (0.52 dSm^{-1}), and OC (1.13%)	pH (7.8), EC (0.36 dSm^{-1}), and OC (1.08%)	Bisht et al. [36]
Rima'a Valley, Yemen	Mixed trees with coffee, *Ziziphus spina-christi* with maize, and *Cordia africana* with coffee	N concentration (0.17–0.26%)	Sole Maize—N (<0.16)	Shoga'Aldeen et al. [32]
Sudan	*Acacia Senegal* + sorghum	BD (0.88 g cm^{-3}), pH (7.49), moisture (9.65%), and OM (1.25%)	Sole sorghum—BD (1.44 g cm^{-3}), pH (6.92), Moisture (9.11%), and OM (0.64%)	Fadl et al. [46]
Ghana	*Bambusa balcoa* + maize (without fertilizer)	Moisture (7.01%), CEC (6.68 cmolc kg^{-1}), total N (0.48 (g kg^{-1}), available P (4.83 (g kg^{-1}), available K (127.60 (g kg^{-1}), pH (6.00)	Sole Maize—Moisture (4.25%), CEC (5.85 cmolc kg^{-1}), total N (0.48 (g kg^{-1}), available P (4.20 (g kg^{-1}), available K (127.50 (g kg^{-1}), pH (5.4)	Akoto [47]
NW India (Haryana)	Wheat–poplar system (alluvial soil)	OC (0.62%), available soil N (205 kg ha^{-1}), P (16 kg ha^{-1}), and K (340 kg ha^{-1})	OC (0.4%), Available soil N (195 kg ha^{-1}), P (10 kg ha^{-1}), and K (295 kg ha^{-1})	Sirohi and Bangarva [33]
New Zealand	Pasture + alder	6% higher total soil carbon mass	Open pasture	Douglas et al. [48]
Niger	Farmer-Managed Natural Regeneration (*F. albida* and *P. reticulatum*) + pearl millet (Arenosol)	pH (5.6), OC (1.25%), Mg (0.27), P (8.28 mg kg^{-1}), and Ca (0.19 $Cmol^{+}$ kg^{-1})	pH (5.26), OC (1.12%), Mg (0.17 $Cmol^{+}$ kg^{-1}) P (3.62 mg kg^{-1}), and Ca (0.14 $Cmol^{+}$ kg^{-1})	Diallo et al. [30]
Niger	*F. albida* in parkland (ferruginous tropical loamy sand)	OC (0.273%), total N (202 ppm), P, and CEC (2.26 meq/100 g soil) (318 ppm)	OC (0.25%), total N (164 ppm), P (310 ppm), and CEC (2.29 meq/100 g soil)	Kho et al. [49]
Mountainous Southeast Guatemala	*Zea mays–Gliricidia sepium* alley cropping	4.3% C and 0.16% total N	Zea mays sole—3.2% C and 0.12% total N	Augustine et al. [22]
Bangladesh	Jackfruit-based agroforestry (Inceptisol)	3.37–9.25% reduction in soil temperature, 10–20% increase in soil moisture, 9–19% enhancement in total nitrogen	Soil temperature (32 °C), soil moisture (11.93%), and total N (0.09%)	Riyadh et al. [26]
Indonesia	*Hevea brasiliensis*–soyabean system (red-yellow podsolic soil)	pH (6.0), OC (1.04%), total N (0.11%), available P (14.31 ppm), K (0.621 me/100 g), Mg (0.61 me/100 g), Ca (2.6 me/100 g), and CEC (19.6 me/100 g)	pH (4.6), OC (0.91%), total N (0.10%), available P (9.46 ppm), K (0.549 me/100 g), Mg (0.51 me/100 g), Ca (0.6 me/100 g), and CEC (10.26 me/100 g)	Rizwan et al. [50]
Ghana	Agroforestry parklands	OC (0.554%), pH (6.1), total N (0.06%), P (13.11 mg kg^{-1}) K (0.337 C mol kg^{-1})	OC (0.34%), pH (5.1), total N (0.4%), P (11.07 mg kg^{-1}), K (0.117 C mol kg^{-1})	Akpalu et al. [29]
Iran	Almond–wheat intercropping (cambisol calcic soil)	OC (0.81%) N (0.074 %), P (11.4 mg kg^{-1}), and K (240 mg kg^{-1})	OC (0.55%), N (0.053%), P (9.15 mg kg^{-1}), and K (172 mg kg^{-1})	Surki et al. [18]

Table 1. *Cont.*

Region	Agroforestry System	Changes in Soil Metrices	Open/Control	Author
Pumice mined areas, Lombok island	*Gliricidia* green manuring (regosol soil)	OC (1.54%), total N (0.11%), CEC (15 cmol kg^{-1}), and BD (1.2 g/cm^{-3})	OC (2.85%), total N (0.08%), CEC (12 cmol kg^{-}), and BD (1.6 g/cm^{-3})	Narendra [39]
Eastern Uganda	Shaded coffee system	Maximum temperature (27 °C)	maximum temperature (32 °C)	Sarmiento-Soler et al. [44]
Yunnan, China	Rubber-based agroforestry	Higher principal components analysis scores for K, Ca, and Mg (-K- 0.82; Ca- 0.81; Mg- 0.5–0.75)	K (0.5), Ca (0.5), and Mg (0.2)	Wu et al. [51]
Semi-arid region of Rajasthan, India	*Acacia leucophloea, Dalbergia Sissoo,* and *Prosopis cineraria* (sandy soil) trees on a farm	microbial biomasses of C (262–320 µg g^{-1}), N (32.1–42.4 µg g^{-1}), and P (11.6–15.6 µg g^{-1})	microbial biomasses of C (186 µg g^{-1}), N (23.2 µg g^{-1}), and P (8.4 µg g^{-1})	Yadav et al. [40]
NW India	A. excelsa-based agroforestry (alluvial)	P and K, Total inorganic N (227.57 µg g^{-1})	Total inorganic N (207.3 µg g^{-1})	Kumar et al. [52]

3. Management of Agroforestry for Soil Improvement

3.1. Species Selection and Density

Trees trap more sand dust than shrubs due to their larger canopies and dense foliage. As a result, the soil beneath trees is likely to be more nutrient-dense than that beneath shrubs. Thus, trees should be favored over shrubs for soil improvement. Augustine et al. [22] suggested that an increase in SOM in agroforestry systems after three years of planting *Gliricidia* improved the soil's nutrients and its ability to support agriculture, but not enough for sustainable production, as this technology alone did not offer enough soil cover to decrease erosion and should be used in conjunction with further management initiatives to lower erosion rates. Additionally, farm management operations such as thinning, trimming, and mulching should be carried out [44]. Wartenberg et al. [23] reported that a rise in tree diversity in complex agroforestry significantly boosted the soil organic carbon at the topsoil but had little effect on the deeper soil layers. According to Eddy and Yang [2], there were not many more advantages to agroforestry for soil health over monoculture, even when the crop diversification is just doubled. The selection of crop species with niche complementarity roles may be more important to agroforestry than species selection advantages from broad crop diversification. Combining species with various root depths, integrating shade-tolerant species beneath the crowns of the foundational trees, and including nitrogen-fixing species into the mixtures to enhance soil nitrogen provision improves the resource-use efficiency of the system [2]. The selection of species with various root structures may facilitate the partitioning of the soil water intake from different soil levels, resulting in less competition and less water loss via deep percolation. Douglas et al. [48] reported 11–18% greater total soil carbon mass rates in open pastures as compared to pastures with poplar systems, whereas pastures with alder systems were 2–6% greater as compared to open pastures, suggesting a choice of proper and suitable species based on the locality and climate for soil improvement. A study by Diallo et al. [30] indicated that under both *F. Albida* and *P. reticulatum*, the soil Na, Ca, P, Mg, P, K, NH_4-N, OC, and pH levels were considerably higher as compared to other tree species and open areas, suggesting that *F. albida* and *P. reticulatum* are more appropriate trees for planting in FMNR (farmer-managed natural regeneration) agroforestry parklands for the improvement of soil fertility, food, and fodder production than any other shrubs or trees. The role of trees in agroforestry systems is determined by a variety of elements, including the species (rooting depth), size and spacing, soil type, rainfall volume and pattern, and dry season severity [53]. *C. africana*'s water intake was mostly centered in the top 90 cm but extended down to

130 cm deep during dry seasons. This indicates that the first 40 cm coincided with the active root zone of the coffee [44]. Still, Sarmiento-Soler et al. [44] did not find any water competitiveness between coffee and banana or coffee and *C. africana*, since the coffee plants' water usage remained static throughout the systems. Bisht et al. [36] compared a wheat–poplar agroforestry system and sole wheat cropping system in Uttarakhand, India, and proved the role of the agroforestry system in the improvement of soil health against climate-related extremities. In the wheat–poplar agroforestry system, the highest pH, EC, available N, and K levels were observed with the *UP-2572* wheat variety, while the highest SOC and available P levels were observed with *DBW-711*. Another study carried out in semi-arid region of Northwest India by Sirohi and Bangarwa [33] reported that higher available soil N, P, and K levels were observed in a 5 m × 4 m geometry than in 10 m × 2 m and 18 m × 2 m × 2 m geometries (paired row) for 7–8-year poplar-based intercropping. Thus, it was recommended that poplar trees be planted at a spacing of 5 m × 4 m as the most appropriate way to improve the soil fertility via the accumulation of leaf litter in the semi-arid and arid areas of Northwest India. Akpalu et al. [29] found that the existing rates of 1.09 and 2.29 trees of *F. albida* per ha in parklands in the Sudan Savannah zones and Guinea, respectively, were insufficient for exploring the full potential of *F. albida* in terms of soil fertility improvements. Thus, there is a need to increase the density on parklands in the Sudan Savannah zones and Guinea to 59 and 37 trees per ha, respectively, to fully achieve fertility improvements among resource-poor farmers, which could add about 100, 3.45, 4.63, and 1698.37 kg ha^{-1} of N, P, K, and OC, respectively, to the soil per year. However, the study by Wu et al. [51] in China warned that in rubber agroforestry, the dense planting of herb species should be avoided, since an increase in the species composition can negatively influence the soil moisture owing to increases in root pores and organic matter, increasing the infiltration and resulting in increased leaching. Such complex, climate-smart, and productive agroforestry systems need robust site- and species-specific knowledge in order to increase their climate resilience [54]. When wheat intercropped with deciduous poplar tree rows was arranged in the north–south and east–west directions in Haryana, higher tree diameter and height growth values were reported in the north–south-oriented tree rows [42]. The windbreak's orientation and the tree spacing can enhance the system's microclimate and ecosystem services, leading to increased production and financial gains in the semi-arid areas of India [42].

3.2. Nutrient Management and Fertilizer Application

In agroforestry, the judicious use of appropriate combinations of organic and inorganic fertilizers promotes soil mineralization and N availability. Kumar et al. [52] reported that the application of FYM @ 10 Mg ha^{-1} + a recommended dose of chemical fertilizer (NPK) effectively stimulates C mineralization in *Terminalia chebula*-based agroforest in the foothills of the Himalayas in India. Thus, the integrated use of organic and inorganic fertilizers should be encouraged in order to improve the C mineralization and inorganic N pools, which can lead to enhanced nutrient availability to plants and higher crop productivity [52]. Another study by Kannur et al. [55] found that the integrated application of FYM, Azotobacter, and PSB on *Capsicum frutescens* under a 2-year-old rubber plantation proved to be better in terms of improving the physical and chemical soil properties under an agroforestry system. Akpalu et al. [29] recommended that it would be financially reasonable to combine an inorganic P source with the organic material in the management of *F. albida* parklands in Ghana because the tree leaf biomass typically contains a higher N/P ratio than that required by the crops, while the P may become deficient in an attempt to supply N via *F. albida* leaf litter application. Manson et al. [56] found lower pH levels in coffee farms using agrochemicals and farms dominated by *Eucalyptus* trees in West Java. Thus, planting native fruit tree species rather than eucalyptus trees as shade trees for coffee plants with the application of organic manure or liming is recommended.

Although higher SOM levels, soil C stocks, total C pools, and total N levels were reported under the coffee–banana system than banana sole cropping in central Uganda, precautions to avoid P depletion should be taken, as under both farming systems the available P levels were limited [57]. Zake et al. [57] suggested the application of well-composted manure @ 20 Mg ha^{-1} per year to solve the soil P limitations. The integration of livestock into their farming systems might be beneficial. The age of the trees, the crown morphology, the phytochemical composition of the litter and its nutrient content, and the root turnover rate determine the improvements in soil properties. Because of the low tannin contents in their leaves, *F. albida* and *P. Reticulatum* decompose more quickly and release more soil nutrients [58]. The potential for agroforestry to restore the land via 'internal restoration' may depend on local circumstances; thus, the proof is inconsistent and inconclusive [59].

The agroforestry ecosystem's soil nutrients would be better managed if the soil mycorrhizae and soil P were fully taken into account [60]. Negative soil conditions, disease concerns, and increased vulnerability to climatic extremes may all lead to agroforestry systems being the best sustainable alternatives.

4. Impact of Agroforestry on Soil Biota

The integration of trees with agricultural crops not only influences the physical and chemical soil properties but also influences the microorganisms present in the soil. The soil microbial population promotes plant growth indirectly because it plays a significant role in enhancing fertility and productivity. As the soil microbial community play an important role in improving fertility and productivity, it indirectly influences plant growth [61]. Soil organisms, particularly microorganisms, play a significant role in plant productivity and health, as well as in nutrient cycling. Comparing agroforestry systems to sole cropping, more soil microbes are present in the soil and they are more diverse and functional. This is expected to result in increased biological soil fertility in these systems. The microbial abundance and soil-related microbial productivity rates are higher in agroforestry systems due to the influence of the trees, the organic matter deposition, the root exudates, the quantity levels, and the diverse litter quality. Nematodes, collembola, acari, diplopoda, earthworms, fungi, and various insects influence C-transformation and nutrient cycling. Soil engineers such as ants, termites, and earthworms play important roles in aggregate formation and in maintaining the soil structure. Centipedes, ground or rove beetles, predatory mites, collembola, and carnivorous nematodes are important for biological control [62].

Falling litter and root exudation provide the necessary energy supply to microbial communities in the form of amino acids, sugars, and organic acids or any other substances [63]. By providing a particular habitat, refugia for epigenic organisms, microclimate heterogeneity, buffering action, soil moisture, and humidity, agroforestry can increase the soil biodiversity as compared to monocropping, with expected effects on the associated ecosystem services. Through various soil-related functions, the soil fauna determine the soil health. *P. reticulatum* boosts the microorganism activity and diversity of nematodes, which enhances the soil OM breakdown, nutrient mineralization, and nutrient enrichment [64].

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 [65]. However, an increase in microbial biomass was confined to rows of trees in alley cropping in Germany [66]. Another study in a temperate agroforestry system reported higher bacterial biomass rates nearby rows of trees in an *Alnus rubra*–maize system [67]. Beule and Karlovsky [68] found that because of the various nutrients being available from root exudation and litter fall, as well as the low fertilization and tillage activities in alley cropping, the composition of bacterial communities in tree rows of poplar–wheat alley cropping systems in temperate climates differed from those in arable land. The integration of rows of trees on farms promotes row-associated soil bacteria that improve the overall diversity in alley cropping, which may also contribute to functional diversity. *Bradyrhizobium* and *Mesorhizobium*, which are N-fixing, were promoted by the trees, whereas the abundance rates of *Nitrosospira* and *Nitrospira* (nitrifying) were lower under the monoculture of trees than in agroforestry systems [68]. A field trial in China by Zhang et al. [69] demonstrated that communities of soil bacteria and fungi in the rhizosphere were influenced by intercropping. The abundance rates of Actinobacteria and Mucoromycota decreased and the Gemmatimonadetes increased in the moso bamboo + *Paris polyphylla* system, while in the moso bamboo + *Tetrastigma hemsleyanum* system, the Acidobacteria and Gemmatimonadetes were significantly higher and the moso bamboo + *Bletilla striata* system enhanced the Acidobacteria as compared to sole bamboo cropping [69]. Matos et al. [70] studied the impact of land uses on soil arbuscular mycorrhizae (AMF) and soil attributes in Brazil and reported that agroforestry, after 8 years of adoption, had led to increased sporulation and species diversity for arbuscular mycorrhizae and glomalin, which is a soil conditioner and binding agent for soil aggregation, which due to microbial growth and activity were promoted by the high addition of relatively high quality and diversified litter in agroforestry systems. Agroforestry favors species with tiny spores such as *Glomeraceae* due to the large input of N from the litterfall [70]. Permanent leaf litter is essential for the existence of soil macrofauna. The species composition in agroforestry systems is correlated to variations in soil respiration [41]. Adopting land use practices such as agroforestry systems, which include extensive and constant plant residue deposition (litter and roots), offers an ecosystem function that is extremely important for glomalin production, soil C protection, and enhanced AMF activity [70]. A 24-year-old *Castanea mollisima–Asima trilobala* agroforestry system showed an intermediate level of microbial biomass C (1.99 Mg ha^{-1}) between a secondary forest (1.7 Mg ha^{-1}) and zero-tillage corn–soybean rotation system (1.36 Mg ha^{-1}) in the USA [2]. However, a study by Zhu et al. [60] in China reported that poplar shelterbelts reduced the diversity of soil fungi, but they found more ectomycorrhizal and fewer harmful fungi than in farmlands. They also found that the relative abundance of *Basidiomycota* increased from 14.72 to 19.18%. In poplar shelterbelts, as opposed to farmlands, the *Inocybe* content was greater while Fusarium was lower. Ectomycorrhizal fungi can develop symbiotic relationships with trees, absorbing carbon from the host and assisting the host in absorbing nutrients such as nitrogen and phosphorus. Fungi that are pathotrophic take nutrients from their host's cells and inhibit the growth of plants [60]. Instead of increasing the alpha diversity, agroforestry systems improve the soil microbial diversity primarily by creating a tree-row-associated microbiome that differs in composition from the crop row microbiome (i.e., greater beta diversity in agroforestry systems) [62]. Zhu et al. [71] found diverse and complex co-occurrences of soil bacteria under male poplar (*Populus deltoides*) trees than in male trees in China, suggesting the higher suitability and potential of male poplar trees for soil biota improvements. Beule et al. [62] reviewed temperate alley cropping systems and found a rise in the number of soil microorganisms in temperate alley cropping agroforestry systems, and this advantageous effect might progressively spread into the crop rows. Several studies have shown an increase in the proportion of fungi, suggesting that they may be more advantageous to fungi than bacteria. Both studies by Banerjee et al. [72] and Beule and Karlovsky [68] did not report an increase in soil bacterial diversity in temperate agroforestry; instead, they found an increase in abundance. Pardon et al. [73] observed greater SOC and soil nutrient contents near trees in a walnut-based alley cropping system in Belgium, which in turn increased the abundance of soil macrodetritivores near the tree rows. However, they reported that the abundance rates of carabids and rove beetles in the arable zone were higher than in nearby trees, which might have been due to the colonizing movement of highly mobile arthropods after hibernation. However, the trade-off between the enhanced soil biodiversity and yield can be partially offset by the alternative revenue from the tree component in the agroforestry system [73].

5. The Use of Agroforestry to Enhance Soil Productivity and Its Management

The fundamental advantage of these tree-based multifunctional land use systems over monoculture agriculture is the resource complementarity between the trees and crops [22]. Plant diversity increases the ecosystem productivity and functioning in natural ecosystems through two mechanisms: (1) the phenomenon of niche complementarity, in which non-overlapping resource requirements or positive associations between species lead to "stable multispecies coexistence"; (2) species selection, wherein the possibility that a species will be extant and provide useful ecological activities or services rises with diversification [2]. The yield of intercrops may be increased due to the favorable modified microclimate, improved soil moisture retention, nutrient deposition through litter, and efficient nutrient cycling [2,17,62,63]. By combining crops and trees, the improved soil health (in terms of the biological, chemical, and physical qualities) enhances the agricultural yields. The gains in SOC were mostly found in the top surface soils, indicating that the improvements to soil health were focused in the rooting zone, where they might have the biggest positive impact on crop yields. Higher SOC and total N concentrations in agroforestry systems might boost the accessible crop nutrients, help to maintain productivity, and minimize the requirement for exogenous fertilizer to keep the cost of cultivation lower [2]. Integrating perennial components in farms promotes food security; contributes to higher crop productivity increases incomes among the smallholder households [74]; and alleviates poverty by providing wood, fruits, fodder, and food directly [75]. The maize grain yield was seven times higher under the canopies of 8-year-old trees and twelve times higher under the canopies of 15-year-old trees of *Faidherbia* in a parkland agroforestry system as compared to outside the canopies [34]. A comparative study of barley and wheat intercropping with almond trees in comparison with the monocropping by Surki et al. [18] in Iran reported 39% and 35% higher grain yields for barley and wheat, respectively, under intercropping systems as compared to sole cropping. *Docynia indica*–forage grass and *Dimocarpus longan*–maize–forage grass systems produced 3.5- and 2.4-fold increases in average yearly income as compared to open maize and *Docynia indica* alone, respectively, after seven years [76]. Das et al. [77] evaluated the performance of broccoli, pea, ginger, and turmeric plants in a Malta-based agroforestry system in the highlands of Bangladesh, and reported the highest B/C ratio in the Malta–broccoli–turmeric system (2.92) and the highest land equivalent ratio (LER) in the Malta–broccoli–ginger combination (2.01), indicating the use of Malta-based agroforestry as a great way to increase economic returns, improve land use and soil fertility, and boost food and nutrition security in the highlands of Bangladesh. Incorporating bamboo plants in alley cropping systems can help smallholders with food security, income diversification, and long-term bioenergy production. The intercropping of cowpea, cassava, and maize plants with *B. Balcoa* led to respective land equivalent ratio (LER) values of 1.37 and 1.54 (cowpea), 1.38 and 1.36 (maize), and 1.12 and 1.19 (cassava) for fertilized and non-fertilized systems in Ghana [47].

Significant increases in the yields of maize and sorghum by 150% and 73%, respectively, under the tree canopy of *F. albida* rather than in open cropping were reported in the literature due to an improved microclimate and buffering action [78]. The adequate pruning of trees led to enhanced light penetration and increased overall yield of maize– *A. acuminata* and *M. lutea* systems in Rwanda [79].

In the current scenario of climate change, climate-related variability negatively affects the livelihood of smallholders; there is a global call for more resilient farming systems for climate change adaptation and mitigation. Integrating fertilizer trees in agricultural land helps to ensure food security and also decreases the chances of crop failure, especially in drought years on resource-poor smallholder farms [34]. In this time of climate vulnerability, reduced soil fertility and rainfall variability and the presence of trees on farms can mitigate the risks of frequent crop failure. The mining of soil nutrients resulting from conventional traditional cropping leads to visible changes in yield patterns through losses of organic matter, SOC, and fertility. Inherent poor soil fertility, insufficient SOC and clay contents, limited means for fertilizer input, crop residue procurement issues for animal and family requirements, variable rainfall rates, and frequent droughts were all prevalent problems in agriculture in arid and semi-arid terrains [80]. Agroforestry practitioners used less inorganic fertilizer and applied it less frequently than non-agroforestry farmers, who used large amounts of fertilizer more regularly [34]. Tsufac et al. [81] reported that the nonpractice of agroforestry is directly related to the usage of inorganic fertilizer, while the adoption of agroforestry practices was inversely related to the usage of inorganic fertilizer, indicating the potential role of agroforestry in helping farmers to reduce their use of inorganic fertilizers while also assisting marginalized smallholder farmers. This reduction in fertilizer input reduces the cost of cultivation and also leads to enhanced income. The total N and soil C contents were comparably higher in the *Gliricidia sepium* alleys than in the control plots in Guatemala [22]. Zhang et al. [82] reported that apricot + millet-based agroforestry can increase the light usage in China's semi-arid regions, contributing to sustainably enhanced soil productivity in China. Bado et al. [83] compared the four-year performance rates of *Pennisetum glaucum* and *Vigna unguiculata* with and without *Ziziphus mauritiana* in Niger and reported that the presence of *Zizyphus* trees improved the water use efficiency rates of millet by 47% and 17% without fertilizer and with FYM, respectively. Several studies cited competition between crops and trees; however, the system's total yield will still increase. This study recommended 80 *Ziziphus* trees per ha^{-1} in a millet field with low inputs as a cost-effective and sustainable approach for smallholders to improve their agricultural productivity and income while managing their soil, soil fertility, and soil-mediated ecosystem services sustainably.

It was reported that the wheat + *Ziziphus* system, which is common in China, led to enhanced land use and economic returns [82]. The income range (excluding the income from tree components) from millet without *Ziziphu*s was $US 414–885 per ha, while with *Ziziphus* the range was US $472–980 per ha over the four years. This increase in income due to the integration of trees may be due to the beneficial impact of trees on the crop yield [83]. Dev et al. [84] suggested the bamboo + sesame–chickpea system (12 m × 10 m) as an excellent livelihood alternative for the semi-arid region of Bundelkhand, India, as this system produced higher LER values of 1.95 to 2.14 and is more profitable than sole cropping or bamboo monoculture. Thus, bamboo-based agroforestry could be used to enhance productivity and economic returns in semi-arid areas of India. Increased average yields for sesame, pear millet, and sorghum were observed in parkland agroforestry areas over a ten-year period in the semi-arid areas of Sudan, and land tenure reforms were needed to influence farmers to retain more trees in parklands [85].

Before integrating any species on a farm, the suitability of any crop combination, as well as the competing behavior for light, moisture, and nutrients between trees and crops, should be taken into account. Integrating drought-tolerant trees with deep root systems or crops with higher light conversion efficiency rates may contribute substantially to improving the land productivity through higher resource capture and efficiency rates. Plants with a wide range of morphological or physiological features should be better suited for agroforestry by occupying different niches [86]. Practices such as the pruning of tree crowns, the use of wide spacing to minimize interspecific competition, or increasing the plant density of mixing crops could be applied for appropriate management [82]. Mantino et al. [87] studied the alley cropping system in Italy and demonstrated that the when the tree–crop distance is less than the height of the poplar trees, the availability of light in the tree rows is important for the soybean yield. They also found that lower light availability in west and east tree–crop interface positions reduced the yield of the intercrop. Applying various management practices such as pruning to allow more light to penetrate to enhance the understory crop yield and the precise application of fertilizer closer to tree rows to retain a higher amount of residue nutrients could reduce the competition for light and promote the more sustainable exploitation of natural resources in agriculture [18]. ICRISAT recommended the microdosing and hill placement of fertilizers as cheaper options for poor farmers, as these options favor biological activity and enhances the root length density by 42–66%, which combined with the effects of the root length density, moisture availability, and absorption of nutrients improves the crop responses [88].

6. Soil Pollution Abatement Potential of Agroforestry

Improper agrochemical management and the mass application of agrochemicals including pesticides and fertilizers in agriculture are significant sources of non-point-source groundwater and surface water pollution globally, and may result in soil deterioration [89,90]. A high root length density in a deeper soil profile is important for the crops because they can make use of water in the subsoil to cope with the dry spells and can also utilize nutrients leached in the deeper soil layer. Agroforestry reduces the use of agrochemicals, leads to accelerated mineralization, and remediates soils and shallow groundwater [91]. Pavlidis and Tsihrintzis [92] reviewed various studies and reported that the roots of trees in agroforestry systems were able to reduce the residues of N and P in the soil by 20–100%, with up to 100% pesticide transport. Among the agroforestry trees, *Platanus* spp., *Populus* spp., and willow tree species are commonly reported to have the potential to absorb contaminants, including pesticides, and can help in their breakdown, immobilizing them in in the woody parts of the trees or leaves (Figure 3) [93]; this potential also varies with the physicochemical properties of the agrochemicals. It should be noted that the tree roots in AFS do not compete with the crops for beneficial nutrients, because due to their depth they only absorb a percentage of the agrochemicals in the deeper soil layers, which may be 60–90% of the applied amount; thus, this decreases the environmental impact of the fertilizers.

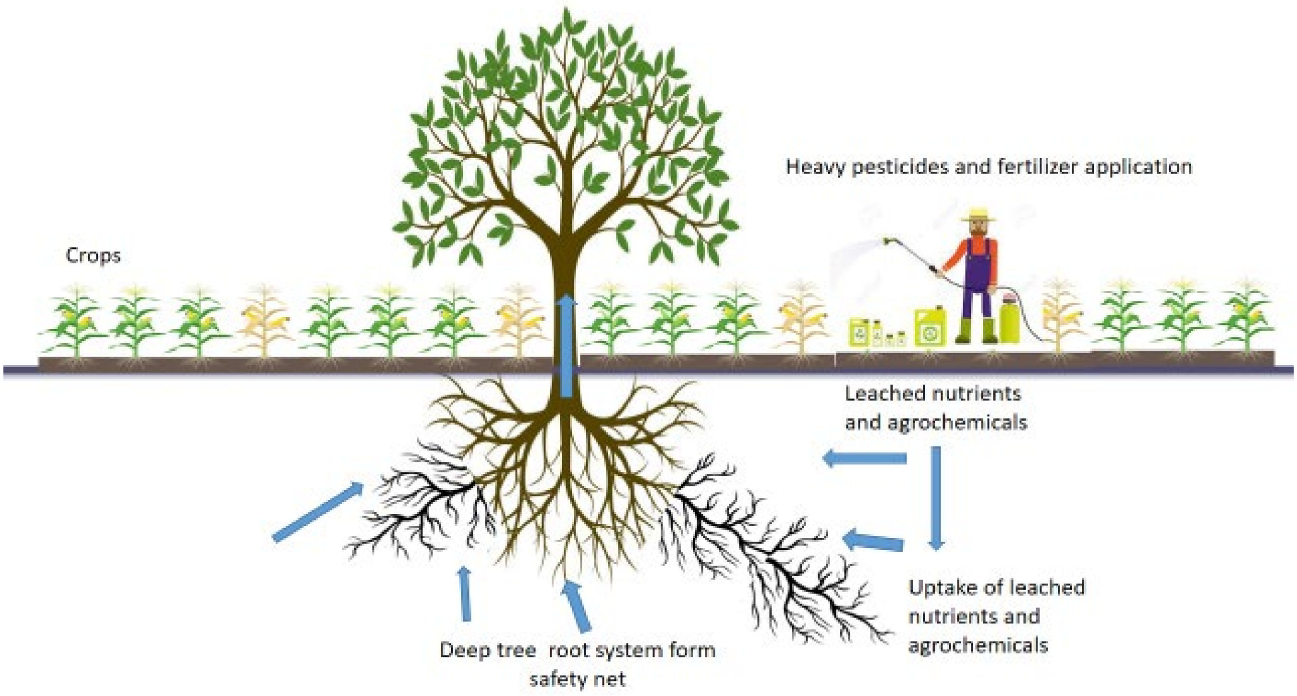

Figure 3. Absorption and immobilization of leached chemicals in agroforestry systems.

Tolerance to pollutants and heavy metals is a prerequisite for phytoremediation. Some species can tolerate, survive, and accumulate pollutants or heavy metals in their roots, stems, and leaves; thus, perennial species are preferred for phytoremediation (Table 2). Hussain et al. [94] compared the performance levels of different species when irrigated with wastewater high in Pb and observed that *Azadiracta indica* accounted for the highest total biomass concentration under municipal wastewater irrigation and the highest Pb concentration under industrial wastewater, followed by *Acacia ampliceps* for Pb; thus, this study suggested that *Azadiracta indica* and *Acacia ampliceps* are candidate species for Pb removal from water.

Table 2. The soil pollution abatement potential of agroforestry systems.

Pollution Abatement	System	Region	Source
Pb contamination	*Azadiracta indica* and *Acacia ampliceps*-based intercropping	Pakistan	Hussain et al. [94]
Leached nutrients	Potato–poplar and maize–poplar systems	Greece	Pavlidis et al. [90]
Leached N and P	Alley cropping	Greece	Gikas et al. [95]
Leached herbicide	Alley cropping	Italy	Borin et al. [96]
Pesticides and herbicides	Maize–olive	Greece	Pavlidis et al. [97]
Leached herbicides and M455H001* (2-methyl-3,5-dinitro-4-(pentan-3-ylamino) benzoic acid)	Wheat–poplar alley cropping	Greece	Pavlidis et al. [98]
Leached N	Pecan–cotton alley cropping	USA	Allen et al. [99]

* Metabolites of the herbicide pendimethalin after degradation in soil.

Through processes of decontamination, hyperaccumulation, and hydraulic lift, the redistribution of soil water by the roots in agroforestry systems removes pollutants and heavy metals from contaminated soil [100]. Pollutants were retained or stabilized in the rhizosphere through a process of phytostabilization. Through phytodegradation, the pollutant is degraded or converted to a less harmful form by plants and whole contaminants are harvested through storage in the leaves or stems of the plant in the process of phytoremediation [101]. The phytoremediation potential is greater in riparian buffers and short woody rotation crops than in other agroforestry systems. Sequential agroforestry systems based on rapeseed (*Brassica napus* L.) (rapeseed followed by *Cajanus cajan*, *Crotalaria juncea* L., or *Gossypium arboreum* L.) significantly reduced the selenium levels in India's contaminated soils. Indeed, *Panicum virgatum* L., a riparian buffer system grass, has the potential to absorb, degrade, and detoxify atrazine in the rhizosphere [101]. The deep root system of the trees that extend below the crops is capable of capturing the excess of agrochemicals by forming a 'safety net'; these agrochemicals might otherwise leak into the surface water or groundwater. Thus, integrating trees on farms, such as through alley cropping, can be a possible pollution abatement strategy. The leaching of nitrogen was reduced by 54% while the leaching of phosphorous was reduced by 50% in an agroforestry system in Greece [95]. Pavlidis et al. [90] studied the pollution abatement potential of potato–poplar and maize–poplar systems in Greece and reported reductions of more than 86% for potassium, 90% for nitrates, 92% for ammonium ion, 85% for nitrites, and up to 100% for phosphates in the potato–poplar system, while the maize–poplar system accounted for reductions of 73% for potassium, a minimum of 77% for nitrates, 77% for nitrites, 97% for ammonium, and up to 100% for phosphates regarding the examined pesticides. Another study in Italy reported 60–100% reductions in herbicides and up to 100% reductions for nutrients in agroforestry systems [96]. A maize–olive system in Greece also demonstrated a reduction in agrochemicals [97], while the herbicides and M455H001 metabolites were reduced by more than 80% and up to 100%, respectively, near trees rather than away from trees in a wheat–poplar alley cropping system in Greece [98]. The reductions in chemicals are faster and more rapid in the deeper layers, exhibiting the 'safety net' phenomenon found in agroforestry. By using the ESAT-A tool, Tsonkova et al. [102] simulated that an approximate 31% potential reduction in nutrients and 47% reduction in pesticides could be possible by using 10% more trees in the field. Additionally, agroforestry reduces the need for pest control and fertilizers and indirectly reduces the application of agrochemicals in agroforestry systems [103]. Allen et al. [99] proved a reduction in groundwater leaching using pecan–cotton alley cropping in the USA. They reported 30–70% higher uptake rates of N at a depth of 0.9 m as compared to cotton, indicating the significance of the root system's influence on N reductions. Based on the application of the Hydrus-2D model, Wang et al. [104] reported that 30.6–40.0% of the total N fertilizer applied to a monocrop is wasted through nitrate loss, while in agroforestry systems, the nitrate loss rates will equal 9.8–31.0% of the total N fertilizer applied.

7. Agroforestry and Soil Erosion

One of the most important environmental issues is soil erosion, causing nutrient weathering and fertility loss and altering the soil structure and texture, impacting the nutrition of plants and their development and adversely affecting the productivity and sustainability of natural and agricultural ecosystems. The most important climatic factor influencing soil erosion and sediment transport is precipitation [105,106]. Various agroforestry systems managed across various regions of the world can decrease runoff and prevent soil erosion to some extent, thereby assisting in the restoration of the environment and providing economic benefits. The practice of these tree-based systems in dryland areas can optimize the development of agriculture via slope stabilization [107]. To reduce soil degradation, the use of agroforestry is an important avenue, as agroforestry systems could buffer the effects of rainfall variability and help retain the soil and soil nutrients [105].

The addition of OM via litterfall and pruning in agroforestry systems contributes to the soil cover and acts as a physical barrier against soil erosion, along with interception via trees directly [100]. Further biomass deposition through root turnover and aboveground litter fall provides food for soil organisms and enhances the biological activity of soil engineers [108], which promotes the soil's structural stability and macroporosity, which are important in reducing soil erosion rates under agroforestry indirectly [109]. The use of agroforestry can maintain the requisite forest cover to ensure hydrological forest functions [110]. Litter maintains the quality of water by filtering soil particles from runoff [111]. Tree-based systems, i.e., "infiltration-friendly" land use systems acting through litter fall, can maintain high infiltration rates by funneling through stem flow [112] and can improve hydrologic functions by providing a crown cover at the tree and understory levels, as well as on the land surface and through water uptake by trees and other vegetation. The canopy cover with the understory vegetation and litter is strongly related to the health of the watershed and limits surface runoff, reduces splash impacts on the soil, and enhances infiltration. In agroforestry, biogenic channels formed by old tree roots, earthworms, and other soil engineers result in macroporosity, which is necessary for infiltration [113]. Canopy retention and interception are the primary defenses against rainfall. Canopy retention prolongs the time of infiltration, while canopy interception leads to direct evaporation through litter fall or stem flow based on the architecture of the leaves and stems [114]. The roots of the trees, the litter, and the understory vegetation reduce the flow velocity of the runoff on the ground and enhance the sedimentation [115]. Agroforestry systems have 75% higher infiltration rates and 57% lower runoff rates as compared to crop monocultures [109]. The diverse and closed distributed root system in agroforestry soil forms more recalcitrant root litter that slowly decomposes, increasing the soil organic carbon accumulation and leading to the formation and preservation of soil transmission pores with improved infiltration [116]. Surki et al. [18] observed lower BD rates, particularly at a distance of 0.5 m from row of trees, in almond-based intercropping results from higher root development and porosity of the soil.

Purwaningsih et al. [117] suggested that trees and crops should be arranged in agroforestry systems according to morphological units formed by the previous landslides, by residual zones, and by erosional and sedimental zones, as different crops and trees have different ecological functions on different units. In addition to ecological functions, the importance of economic and social values should also be considered when selecting the appropriate trees and crops for erosion control (Figure 4). Beliveau et al. [105] studied erosion in various systems in Brazil and reported that the eroded soil particles, namely mobilized amounts of mercury, Ca, Mg, and K, were similar in a 2-year-old agroforestry system and mature forest system but were significantly lower as compared to a continuous cropping system due to ground cover, as most of the erosion is strongly related to ground cover, which reduces erodibility. They revealed the potential of agroforestry for maintaining integrity and reducing erosion, even in the early stages of establishment. The ground cover in agroforestry acts as a barrier to absorb the impact of raindrops on soil, limiting the detachment and transport of soil. It was reported that coffee-based agroforestry reduced erosion and surface runoff more than sole coffee cropping [118]. It was reported that the runoff rates were 2655 m^3 ha^{-1} in agroforestry, 3067 m^3 ha^{-1} in grass buffer, and 5598 in control systems, while total the N loss was 1.85 kg ha^{-1} in the agroforestry as compared to 7.47 kg ha^{-1} in the control system in the period of 2004–2008 in the USA [115]. It was proven that traditional agroforestry was equally effective in controlling soil erosion, such as using terracing, a type of engineering structure that prevents sediment detachment, in the West Usambara Mountains, Tanzania [119]. Muchane et al. [109] estimated the worth of soil-mediated ecosystem services rendered by agroforestry and found that the agroforestry system exhibited a 50% lower soil erosion rate than the monoculture system. Du et al. [1] compared the performance of agroforestry against other conservation agricultural practices and found that compared to erosion measurements under residue returns, reduced tillage, and no-tillage, the use of cover crops and agroforestry was linked to the biggest reductions in erosion. The rise in surface litter brought on by perennial plants might aid in reducing splashing and soil detachment, while the inclusion of tree trunks in AF systems can lower runoff rates and consequently diminish the sediment-carrying capacity. Perennial tree cover may be beneficial in lowering the erosive force of rainfall, and some tree species can also add hydrophobic chemicals to the soil, which can affect the infiltration rates and surface runoff [1]. By capturing raindrops, increasing transpiration and water retention in the soil, delaying runoff, and encouraging infiltration, trees can modify how water is cycled through the environment [120].

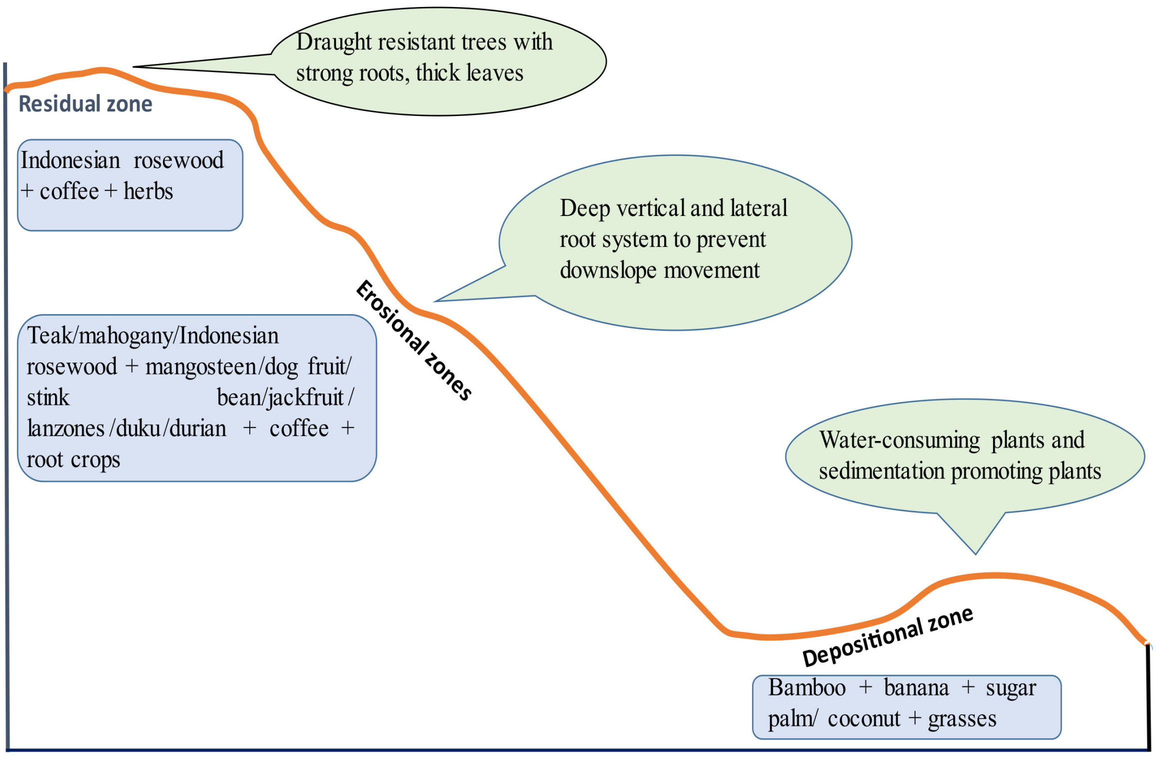

Figure 4. The trees and crops arranged in an agroforestry landscape according to morphological units formed by the previous landslide (source: adapted and modified from Purwaningsih et al. [117]).

Along waterways, riparian buffers are implemented to minimize the soil erosion risk, nutrient leaching, and habitat loss. Windbreaks reduce erosion and enhance the availability of water to the adjoining crops by lowering the evapotranspiration. Kinama et al. [121] found that the mulching of runnings from hedgerows of *Senna siamea* minimized soil loss from 100 Mg ha^{-1} in sole maize to 2 Mg ha^{-1} and the runoff from 100 mm in sole maize to 20 mm only in 15% sloppy alfisol in Kenya. This compromise between the erosion reduction and crop yield does not have to be a major constraint in practicing agroforestry, as trees also provide other significant benefits to farmers, while engineering structures require high investment costs as compared to inexpensive agroforestry. Agroforestry has the potency to be productive while also maintaining a wide range of biological, physical, and soil-related ecosystem services by mimicking nature's functions. Thus, agroforestry could be the next move in sustainable farming [122].

8. Agroforestry for Degraded Soil and Arid Areas

Environmental regulations suggest the use of agroforestry as a practical solution for the restoration of degraded landscapes, to meet obligations under international agreements, for greenhouse gas mitigation, to transition to low-C agriculture, and also to improve food security worldwide [70]. Rodriguez et al. [123] suggested various agroforestry systems for enhancing carbon in the degraded soil of the Colombian Amazon, as introducing trees in pastures enhances the bioengineers in the soil, resulting in the formation of biogenic macroaggregates in the soil with high carbon rates. The formation of soil aggregates is important for nutrient cycling, as well as for the carbon cycle, as it acts as a C sink. Soil aggregates comprise biogenic, physical, and root aggregates. The formation of physical soil aggregates is slower as compared to biogenic aggregates (Figure 5). By hosting a greater population of bioengineers, agroforestry systems store more OC through the formation of biogenic aggregates as well as root aggregates via root decay [124]. Thus, in degraded soil, agroforestry can revive soil-based ecosystem services. A study in Bangladesh by Chowdhury et al. [125] reported that agroforestry plots had considerably greater SOM (4.75%), available P (12.17 µg g^{-1}), and exchangeable K (0.39 mg kg^{-1}) concentrations than reforestation, afforestation, or slash-and-burn plots (sandy loam and clayey soil). In regions formerly subject to slash-and-burn techniques, agroforestry systems have the potential to enhance soil fertility to a higher level as compared to restoration via afforestation. The use of agroforestry systems is a viable strategy for managing slash-and-burn land sustainably. The use of agroforestry systems allows the preservation of biological diversity and other soil health indicators, with implications for their potential use in the future to restore degraded land areas [70]. An agroforestry system had 15% higher SOC and N stocks and higher microbial biomass C and N contents than a nearby no-till corn–soya rotation system, indicating that the integration of woody perennials in farms is more effective for the improvement of soil health than no-tillage cropping in Fayette silty loam soil in the USA [2].

Managing N-fixing trees on farms, commonly known as fertilizer trees, in agroforestry systems in African regions can potentially help sustain crop yields, maintain nutrient cycling, restore soil fertility, and conserve the SOC through the decomposition of the litter fall and through root and microclimate creation. Fertilizer trees shed leaves before the rainy season and make nutrients available after decomposition at the peak period of requirement. It was observed that the average leaf litter fall rates for two seasons were 1.6 Mg ha^{-1} from 8-year-old, 1.7 Mg ha^{-1} from 15-year-old, and 3.8 Mg ha^{-1} from 22-year-old trees of *Faidherbia albida* on a DM basis in an agroforestry system in Zambia, which provided annual additions of C, N, P, and K of 0.7–1.6 Mg ha^{-1}, 34–83 kg ha^{-1}, 1.8–4.3 kg ha^{-1}, and 10–26 kg ha^{-1}, respectively, and could fulfill 30–71% of the N, 10–25% of the P, and 60–100% of the K needs of crop the if the litter was the only nutrient source [34]. The meta-analysis by Muchane et al. [109] assessed soil-mediated ecosystem services from agroforestry and found that the agroforestry system exhibited a 50% lower soil erosion rate, 21% more SOC, 13% more N storage, 46% more available N, 11% more available P, and 2% higher pH as compared to monoculture systems due to improved infiltration, less runoff, a greater proportion of soil macroaggregates, and improved structural stability of the soil under agroforestry. Yengwe et al. [34] found that the soil (sandy loam) under the canopy of *Faidherbia trees* in an agroforestry system in Zambia had 26% higher mineral N, three-fold higher available K, 43% higher total N, 31% higher SOC, and a lower C/N ratio than outside the canopy. The mineralization rate was higher under the canopy due to the lower C/N ratio than the outside canopy. The annual leaf litter fall rates were 340 g m^{-2} y^{-1} in the Guinea Savannah zone and 264 g m^{-2} y^{-1} in the Sudan Savannah zone in *F. albida*-based parkland agroforestry systems in Ghana [29].

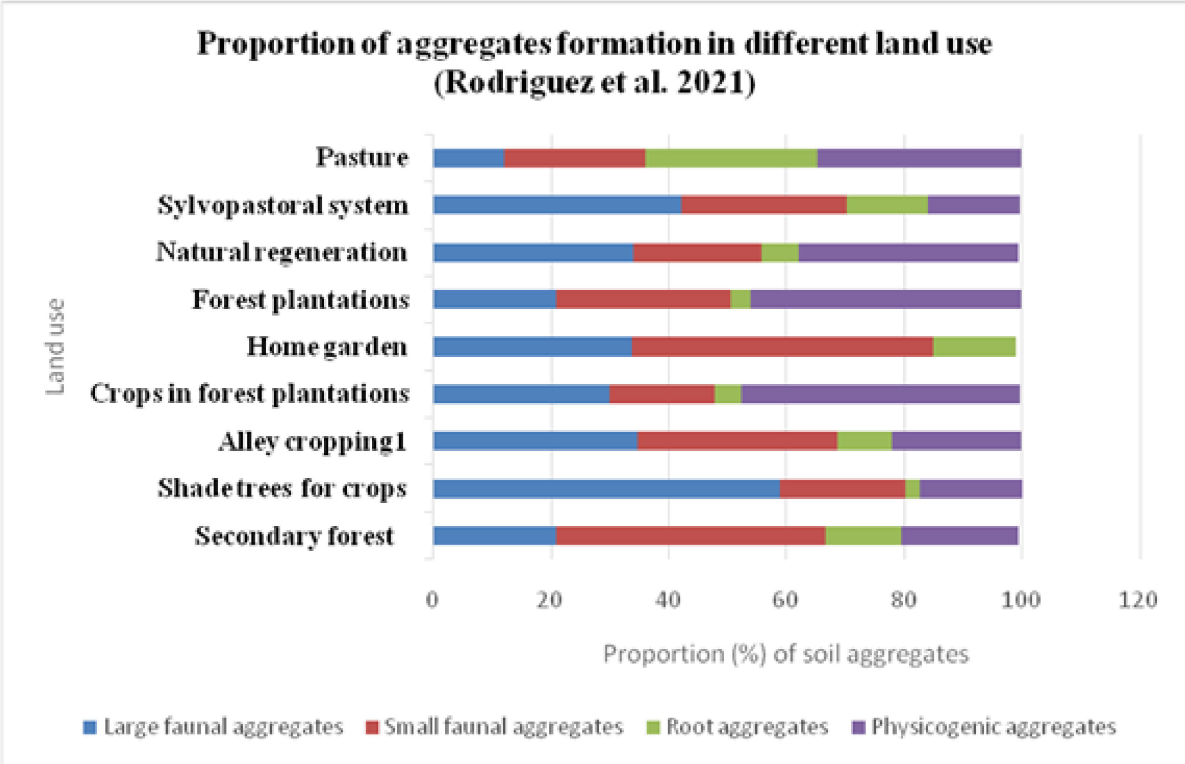

Figure 5. Proportions (%) of aggregate formation (by mass) from various land uses in the western Colombian Amazon (source: adapted and modified from Rodriguez et al. [31]).

Akpalu et al. [29] studied soil fertility indicators in parkland agroforestry systems in Ghana and reported higher SOC and soil N rates under *F. albida* canopies than outside the canopies. The SOC content in the mid-canopy was 0.55%, which decreased with increasing distance from the stems of mature *F. albida* trees to 0.41% at the canopy edge and further reduced to 0.34% 5 m from the canopy edge. The high leaf litter drop, followed by rapid degradation and mineralization at the start of the cropping season due to reverse phenology, deep rooting habits, and the presence of nutrient-rich leaves due to N-fixation, resulting in the albida effect, makes *F. albida* a prospective candidate tree for the improvement of soil and crop productivity in smallholder farming systems in Africa's semi-arid and arid areas [29].

Rizwan et al. [50] proved that an agroforestry system based on *Hevea brasiliensis*, *Gmelina arborea*, *Melia azedarach*, and *Anthocephalus cadamba* with soybean in Indonesia may increase the soil's chemical fertility by improving the pH, OC, total N, available P, potassium, sodium, and calcium levels in red-yellow podsolic ultisol. Saputra et al. [59] evaluated the 'internal restoration' potential of agroforestry systems in degraded soil areas in Indonesia and reported higher soil macroporosity, root length, and weight values in the topsoil (50% of that found in degraded forests) in soil areas under complex agroforestry systems than in other agricultural systems; although not adequate to replicate forests, this study found that the use of complex agroforestry improves the soil structure of degraded soil areas caused by forest conversion when compared to other agricultural systems. Because of the rich litter content of bamboo, Akoto et al. [47] recommended use a bamboo agroforestry system for the reforestation of degraded forest soils (sandy loam and ferric acrisol) in Ghana, because the cation exchange capacity (CEC), soil moisture, pH, N, available P, and K rates are enhanced in bamboo-based agroforestry systems compared to monocropping, which could help in maintaining and improving the physical, chemical, and biological soil properties through the return of nutrients to the soil [126]. The potassium concentration of bamboo litter, for example, has been shown to be critical in bamboo agroforestry systems because it functions as a soil amendment catalyst [127]. Sirohi and Bangarwa [33] compared an 8-year-old poplar-based agroforestry system with wheat monocropping and found that the SOC, EC, pH, available soil N, available P, and available K rates increased significantly under different spacings of poplar-based intercropping as compared to wheat sole cropping in alluvial soils of the semi-arid areas of northwest India. Diallo et al. [30] examined the effects of trees and shrubs on the chemical properties of the soils (arenosol) in semi-arid areas of Niger and reported that the pH, OC, NH_4-N, P, Na, K, and Ca levels were consistently greater immediately under the crown than in the crown neighborhood (outside canopy); further, the soil nutrient contents were higher and reduced with the soil depth, independent of the tree type or nutrient level. The availability rates of the P and N were respectively 30% and 200% higher in sandy loam soil under the *F. albida* canopy than in the outside areas, resulting in a 2.5-fold higher millet yield under the *F. albida* canopy in Niger [49]. A *Gliricidia*-based agroforestry system exhibited the highest peak adoption level of 67.6% in twelve years in one participatory research study carried out among farmers in Tanzania [128], and this study also found that the cost of investment is an important variable for the peak adoption upfront for *Gliricidia*-based agroforestry and fertilizer technologies. Thus, to make farmers' access to inputs easy and at a cheaper cost, awareness among farmers regarding the long-term non-cash environmental value of the agroforestry system is needed to lure smallholders to practice agroforestry approaches.

Ramirez et al. [129] 2022 evaluated the soil quality index values of various land uses in the Philippines and reported the following trend according to the findings: forest (76.39%) > agroforestry (76.21%) > agriculture (49.43%). Matos et al. [130] assigned Soil Management Assessment Framework (SMAF) scoring values to various land uses and discovered that the total SMAF scores were 0.87–0.88 for agroforestry systems, 0.83 for degraded pasture, and 0.82 for the secondary forest, with significant differences amongst the land types. It was discovered that the annual growth rate of the soil C stock was around 11% in an agrosilvopastoral system (the Iberian Dehesa system in a Mediterranean climate), far exceeding the proposed '4/1000 Soils for Food Security and Climate' initiative for enhancing soil carbon, which is critical for maintaining soil fertility and agricultural production [131]. Agroforestry, an ecologically driven, dynamic tree-based system that incorporates multiple-use trees on farms, can boost productivity and provide resiliency against the unpredictable impacts of climate change in degraded and arid areas around the world [120].

9. Conclusions

The integration of trees with agricultural crops with proper species selection and management practices helps in improving the soil structure of degraded soil, as well as the biological, chemical, and physical properties of the soil, through its ability for microclimate modification. Trees on farms improve infiltration and positively impact hydrologic functions through litter fall and canopy effects. Agroforestry enhances the soil-related microbial activity via the influence of the trees, organic matter deposition, the presence of root exudates, and the diverse litter quality, which help in enhancing the soil quality. Agroforestry systems buffer the impact of rainfall, reduce the erosion of the soil and nutrients, and help in minimizing soil degradation. The addition of this perennial component in agriculture could be a possible pollution abatement strategy against agrochemicals and pollutants. Thus, there is a need for awareness among farmers regarding the long-term non-cash environmental value of the agroforestry systems to lure smallholders to practice agroforestry approaches. Agroforestry can restore soil-based ecosystem services in degraded soil and provide a viable pathway for intensification to make agriculture more sustainable because of its nutrient pumping and cycling, litter fall, and microclimate effects and its influence on the soil biota. In the current scenario of climate change, climate-related variability negatively affects the livelihoods of smallholders, as well as the soil conditions, with higher disease risks and higher susceptibility to climate change. There is a global call for the implementation of agroforestry systems as more sustainable and resilient farming systems.

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