https://doi.org/10.56556/jase.v2i1.799

REVIEW ARTICLE

A review of agroforestry as a sustainable and resilient agriculture

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Received: 28 March, 2023, Accepted: 22 May, 2023, Published: 26 May, 2023

Abstract

The agricultural sector is confronted with the formidable challenge of providing sustenance for a global population of 9 billion individuals by the year 2050, all the while mitigating adverse ecological and societal impacts. An attempt to address this difficulty has been made through the implementation of organic farming practices, which have yielded predominantly favorable results. Nevertheless, there are still certain obstacles that need to be addressed. Organic agricultural practices exhibit lower yields compared to conventional methods, while concerns persist regarding greenhouse gas emissions and fertilizer leaching. This paper provides an overview of existing organic and conventional agriculture systems and proposes that agroforestry, a deliberate integration of trees and shrubs with crops or livestock, may represent a promising avenue for advancing sustainable agriculture. Agroforestry possesses the capacity to sustain productivity and concurrently provide many ecosystem services through the use of nature-inspired methods. This study presents an overview of the prevalent methods and products associated with agroforestry, while also highlighting the positive environmental and social impacts it brings about. The present study aims to examine the obstacles encountered in the implementation of agroforestry practices and to suggest potential strategies for policy modification that could enhance the uptake of such practices among farmers. The findings of this review study indicate that agroforestry emerges as a very effective land use strategy for addressing both food security and environmental degradation concerns.

Keywords: Agroforestry; Organic agriculture; Land use; Agroecology; Food security; Environmental sustainability

Introduction

The field of agriculture exerts a significant influence on the Earth's ecosystem (Bishaw et al., 2022; Raihan, 2023a). According to Ahmed and Ambinakudige (2023), around 38% of the Earth's land surface is allocated for agricultural purposes, rendering it the most significant anthropogenic land utilization. The primary driver of deforestation and the subsequent loss of native habitats is the expansion of agricultural land (Begum et al., 2020; Jayathilake et al., 2021). This phenomenon has resulted in the collapse of various wildlife populations, including avian, insect, and mammalian species, some of which are currently classified as endangered (Shah et al., 2022). The process of nutrient leaching from fertilizer contributes to the phenomenon of eutrophication in water bodies, hence causing the formation of oxygen-depleted areas known as "dead zones" in various aquatic environments globally (Zahoor & Mushtaq, 2023). Agriculture stands as the primary anthropogenic source of greenhouse gas emissions, which have been linked to climate change. The impacts of these repercussions are not exclusive to the human population.

Derouiche et al. (2023) have observed the presence of detectable levels of pesticides in several habitats, including the human body. The economic burden of pesticide poisoning in the United States has been approximated to be $1.2 billion annually (Donley, 2019). Additionally, the presence of excessive nitrate in drinking water resulting from over-fertilization can lead to health issues and necessitate costly remediation efforts (Zahoor & Mushtaq, 2023). In addition to the potential environmental and societal consequences, the resilience of our agricultural systems is also a matter of concern (Dipu et al., 2022; Raihan & Tuspekova, 2022a). According to Xu et al. (2022), a mere fifteen crops are responsible for generating 90% of the global food calorie supply. Among these crops, wheat, rice, and maize alone contribute to 60% of the total food calories. The cultivation of the majority of these crops predominantly occurs in expansive areas characterized by yearly monocultures, hence posing a significant susceptibility to pest and disease outbreaks (Khatri et al., 2023). The Irish potato famine, which occurred from 1845 to 1850, resulted in the loss of more than one million lives. This historical event serves as a poignant illustration of the consequences that might arise when a singular crop, upon which a population substantially depends, is devastated by disease (Read, 2022). Monocultures necessitate annual replanting, substantial resource inputs, and weed management (Zhang et al., 2023). It has been posited that this repetitive pattern of planting, fertilizing, and spraying primarily benefits major agribusiness corporations that provide the necessary inputs, rather than effectively addressing global food security objectives (Gerhardt et al., 2022). In order to ensure the enduring viability of an agricultural system, it is imperative that the soil maintains its productivity and that the essential inputs remain accessible in subsequent periods (Paul et al., 2023). Nevertheless, it is important to note that in numerous agricultural settings, the rate of soil loss surpasses that of soil formation, leading to a deterioration in the quality of the remaining soil (La et al., 2023). The agricultural sector is vulnerable to variations in fuel pricing and supplies due to its significant dependence on fossil fuels, particularly in the form of liquid fuel and fertilizer (Majeed et al., 2023; Raihan, 2023b). Simultaneously, the unidirectional flow of fertilizer nutrients contributes to both pollution and scarcity. Phosphorus serves as a pertinent illustration in this context. This indispensable nutrient for plants is projected to undergo a rise in mining and processing costs. Concurrently, the discharge of phosphorus into water bodies contributes to the phenomenon of eutrophication (Mancho et al., 2023).

In the foreseeable future, it is anticipated that our agricultural systems will need to undergo adjustments in response to a shifting climate, characterized by an augmented occurrence of severe weather phenomena such as droughts and floods (Brick et al., 2022; Raihan, 2024a). Furthermore, there is an expected rise in the prevalence of diseases and pests affecting agricultural production (Balasundram et al., 2023). The impact of climate change is expected to be more pronounced in developing regions due to socioeconomic factors such as poverty, which might impede individuals' capacity to effectively respond and adapt (Bedeke, 2023; Raihan, 2023c). The Dust Bowl phenomenon that occurred during the 1930s serves as an illustrative case of the detrimental outcomes resulting from unsustainable farming methods in conjunction with an unprecedented period of severe aridity (Yuan et al., 2023). The collapse of civilizations, such as the ancient Mesopotamians and the Mayans, can be attributed to agricultural overreach and the failure to effectively respond to climate change. The agricultural sector is confronted with the formidable challenge of providing sustenance to a global population of 9 billion individuals by the year 2050, all the while mitigating detrimental impacts on the environment and society (Wijerathna-Yapa & Pathirana, 2022; Raihan, 2023d). Hence, the primary objective of this study is to critically examine the existing organic and conventional agricultural systems, while proposing agroforestry as a potential advancement towards achieving sustainable agriculture. Agroforestry possesses the capacity to sustain productivity and concurrently provides many ecosystem services through the use of systems that imitate the activities observed in nature. This study provides an overview of the prevalent methods and products associated with agroforestry, while also highlighting the positive environmental and social impacts that result from its implementation. This study additionally examines the obstacles encountered in the implementation of agroforestry practices and investigates potential strategies for modifying policies to enhance farmer engagement and uptake. This review study could provide valuable insights for the development of agricultural and environmental policies aimed at promoting food security through effective land use management, while also mitigating environmental degradation and the adverse effects of climate change.

Methodology

The objective of this study is to assess the potential impact of agroforestry on global sustainability, with a specific focus on ensuring food security and improving environmental quality. The present study employed the systematic literature review methodology as suggested by Tawfik et al. (2019). The systematic literature review framework is considered to be a dependable approach (Benita, 2021; Raihan & Bijoy, 2023; Raihan & Himu, 2023; Raihan, 2023e; 2023f; 2023g). A preliminary review of the literature was conducted to identify pertinent articles, validate the proposed idea, avoid redundancy with previously covered issues, and ensure the availability of sufficient articles for conducting a comprehensive analysis of the subject matter. Moreover, the focal point of the themes should revolve around the inquiries on the significance of agroforestry in ensuring food security and improving environmental quality. According to Tawfik et al. (2019), it is crucial to enhance the retrieval of results by acquiring a comprehensive understanding and familiarity with the study topic through the examination of pertinent materials and active engagement in relevant debates. This objective can be achieved by conducting a thorough examination of pertinent literature and actively participating in pertinent academic conversations.

The present study examined various strategies aimed at mitigating the influence of prejudice. One of the methods employed was performing a systematic manual search to identify any document that might have been missed during the original search process. This investigation, employing the methodology employed by Vassar et al. (2016), discovered no discernible indications of bias. In the context of this investigation, a comprehensive set of strategies was employed to carry out manual searches. The method employed encompassed many strategies, such as conducting an exhaustive literature search to identify relevant references from the studies and reviews under consideration. Furthermore, supplementary materials, including related papers and articles cited within reputable academic databases such as Google Scholar, Scopus, and Web of Science, were thoroughly examined. The manual search results were initially enhanced and polished through the process of examining the reference lists of the included publications. The initial stage of the process was undertaken. Subsequently, the author engaged in the practice of citation tracking, a method involving the systematic monitoring of all the scholarly works that reference each of the papers incorporated in the collection. In conjunction with the manual search, an online search of databases was also undertaken as an integral component of the comprehensive search process.

This study exclusively relied on research articles published in peer-reviewed journals, ensuring the reliability and validity of the findings. The results of this study serve as a valuable basis for future research endeavors that aim to explore the potential impact of agroforestry on achieving sustainability, with a specific focus on ensuring food security and improving environmental quality. Both qualitative and quantitative secondary literature on agroforestry were considered. The publications were thereafter evaluated to ascertain whether their main subject matter bore a resemblance to that of the present inquiry. Priority consideration was given to papers published after the year 2000. The primary justifications for the elimination of papers are their lack of relevance, duplication, incomplete textual content, or limited presence of abstracts. The predetermined exclusion criteria were established to safeguard the researcher against potential biases that could influence their findings. Figure 1 illustrates the progression of review criteria employed for the selection of suitable documents for review analysis.

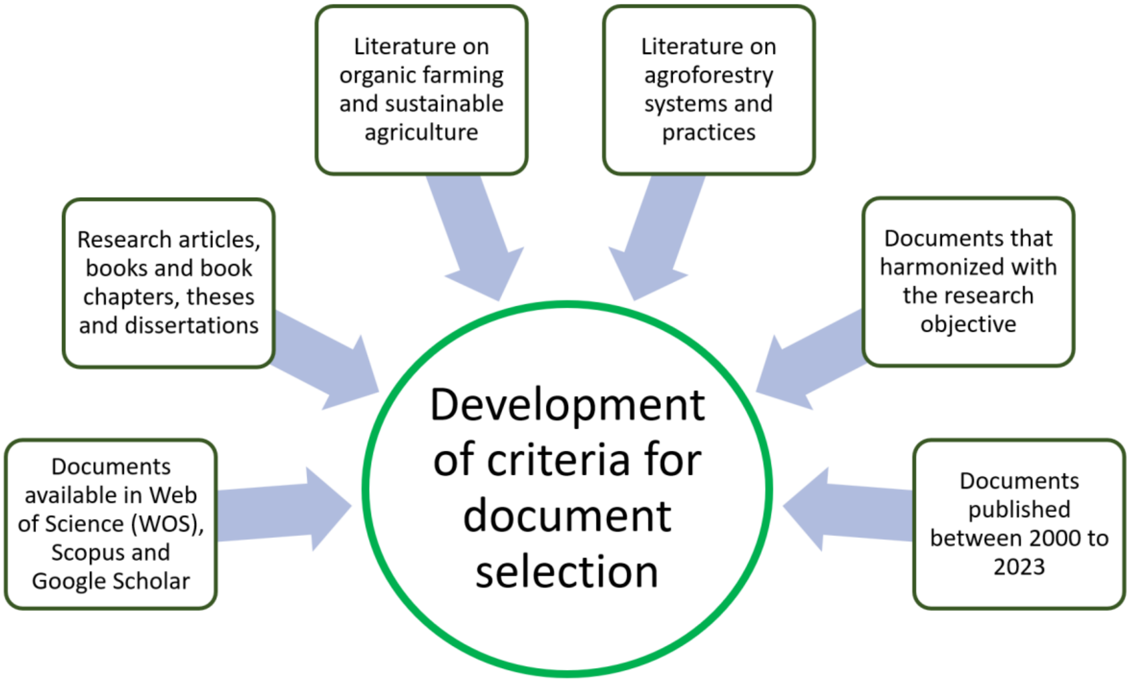

Figure 1. The development of criteria for the selection of documents.

The initial search with the keywords led to 4463 documents. After scanning the documents based on the selection criteria and to remove possible duplication, 512 articles were selected for the next step of scanning. After screening those article's titles and abstracts, the comprehensive literature review encompassed a total of 146 distinct scholarly articles. The present study implemented a data verification process, wherein each included article was cross-checked with its corresponding entry in an extract sheet using visual evidence. It is noteworthy to mention that of the 146 papers subjected to qualitative synthesis, only those publications containing relevant material were cited in the reference list contained in the manuscript. This implies that certain articles were not included in the reference list. Figure 2 illustrates the systematic review procedure utilized in the current study. After the research topic was chosen, this study proceeded to find and locate relevant articles, do an analysis and synthesis of diverse literature sources, and create written materials for article review. The synthesis phase encompassed the collection of a wide range of publications, which were subsequently amalgamated into conceptual or empirical analyses that were relevant to the finalized research.

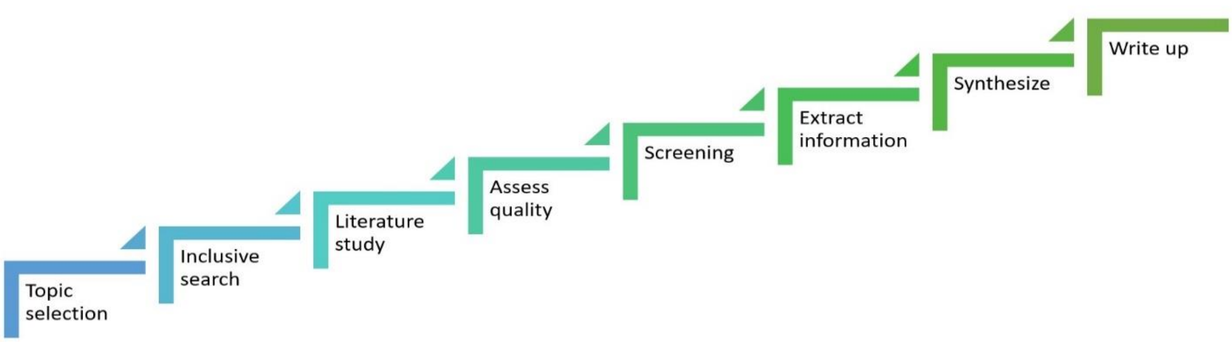

Figure 2. The procedure of systematic review conducted by the study.

Organic Farming and Associated Challenges

The emergence of organic agriculture can be attributed to its role as a viable alternative to the prevailing conventional farming paradigm. While there may be subtle variations across countries and certification agencies, the primary principles governing organic management generally entail the prohibition of synthetic pesticides and fertilizers, genetically modified organisms (GMOs), and the preventive application of antibiotics in cattle feed (Mie et al., 2017). In order to preserve soil quality, it is imperative to employ a range of strategies, including but not limited to crop rotation, cover cropping, and mulching (Crystal-Ornelas et al., 2021). According to Davis et al. (2022), animals that are managed under organic practices are required to consume feed that has been certified as organic. Additionally, ruminant animals must be provided with a designated amount of time to access pasture. The maintenance of fertility in agricultural systems is commonly achieved by the utilization of leguminous cover crops, the application of organic materials like manure and compost, the use of biologically generated inputs such as blood and feather meal, and the incorporation of mined mineral compounds (Tei et al., 2020).

The management of weeds in organic grain and vegetable systems typically involves the utilization of tillage as a primary control method. However, it is worth noting that cover cropping and crop rotation also hold significant importance in disrupting weed cycles (Pantović & Sečanski, 2023). The management of pests involves the implementation of strategies such as the provision of suitable habitats for advantageous predators, the careful selection of plant stock that exhibits resistance, and the utilization of biologically produced pesticides as a final recourse, if necessary (Monteiro & Santos, 2022). The implementation of organic production standards typically results in better sustainable outcomes in practical applications (Raihan et al., 2023a). According to Beaumelle et al. (2023), organic farms have been found to support greater levels of biodiversity compared to conventional farms. This enhanced biodiversity encompasses various organisms such as insects, plants, soil biota, as well as avian and larger animal species. According to Pergner and Lippert (2023), organic farms frequently exhibit greater diversity in their cropping systems as a result of including livestock and implementing longer crop rotations. According to Monteiro and Santos (2022), the implementation of mechanical and cultural control strategies in managing weeds and pests can result in residual populations at reduced levels, hence promoting biodiversity. According to Prout et al. (2021), the implementation of organic management practices has been observed to enhance soil quality, as indicated by measures of soil organic matter. However, it is worth mentioning that several studies have reported the highest levels of soil quality in the context of no-till conventional agriculture (Montgomery et al., 2022). While conventional farming often outperforms organic farming in terms of yields, research has demonstrated that in drought years, the situation can be reversed. This phenomenon is related to the superior water retention capabilities of soils managed under organic practices (Martín-Lammerding et al., 2021). In general, organic production demonstrates a lower energy consumption per production unit as a result of the elevated energy expenditures associated with conventional fertilizers and pesticides (Mousavi et al., 2023).

It is important to acknowledge that while organic certification imposes strict criteria for the application of pesticides, synthetic fertilizers, and GMO technologies, both conventional and organic growers have access to a diverse range of techniques that can yield positive environmental results. Cover cropping, integrated pest management, the application of manure and composts to enhance soil organic matter, crop rotation, and the integration of livestock and crops are crucial strategies that warrant careful consideration when assessing their benefits. Several studies have examined the comparison between organic and conventional crop systems and have found that the observed enhancements in organic management can be attributed to specific practices such as the application of manure and the implementation of cover cropping. These practices, which are integral to the organic system, have the potential to yield similar benefits if adopted in a conventional system (Scavo et al., 2022; Chinthalapudi et al., 2023). Figure 3 illustrates the fundamental concepts and resultant impacts of organic farming.

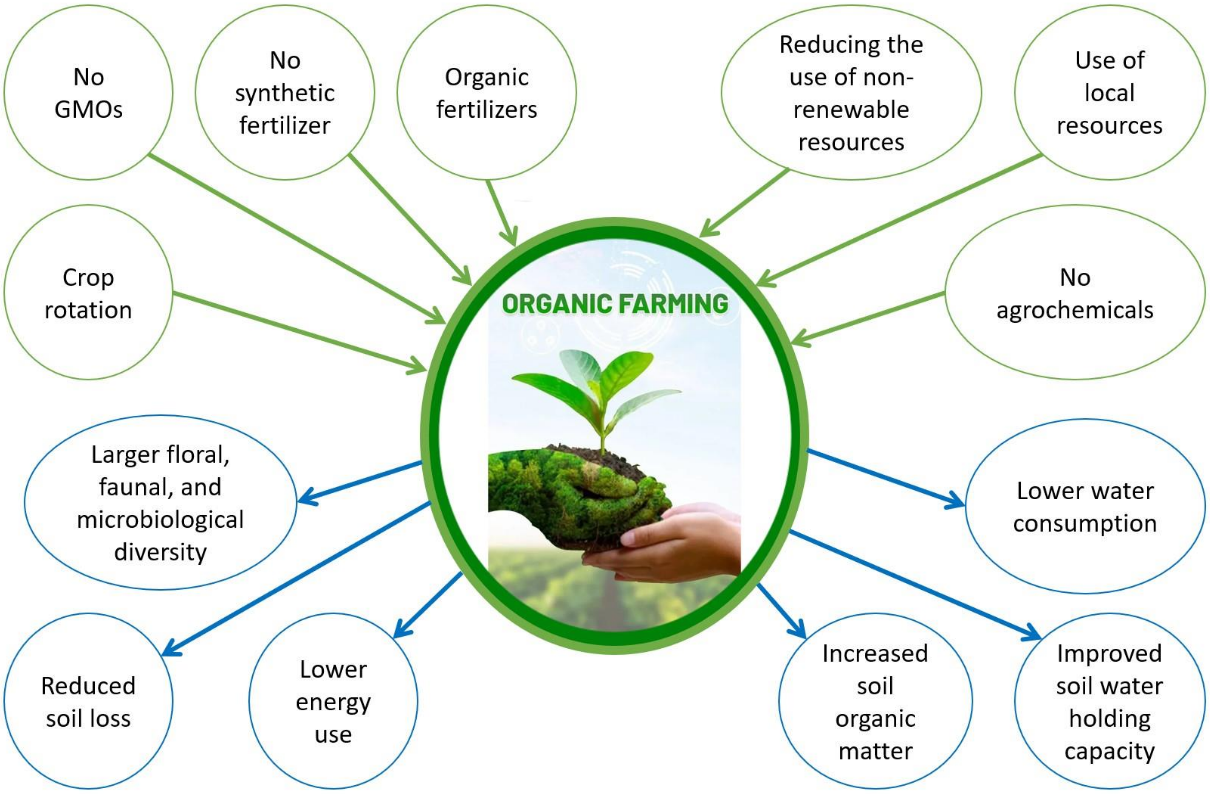

Figure 3. The fundamental concepts and resultant impacts of organic farming.

Nevertheless, despite the commendable goals underlying organic certification methods, it is worth mentioning that a significant number of organic crop production systems employ similar fundamental methodologies as conventional farming, hence potentially resulting in comparable adverse outcomes (Telwala, 2023). The practice of producing annual monocultures, which necessitates annual replanting, the use of fertilizers, rigorous weed management, and the employment of mechanical equipment, has exhibited limited alteration, particularly when implemented on a broader scale beyond local market gardens (Feng et al., 2022). The substitution of conventional instruments with less detrimental alternatives is evident in the adoption of organic seeds in place of genetically modified organism (GMO) seeds, the utilization of cultivation or mulch as alternatives to pesticides for weed management, and the implementation of cover crops and manure as substitutes for fertilizers derived from fossil fuels (Caporali, 2021). While these modifications have the potential to reduce environmental impacts, it is important to note that complete elimination of such problems may not be achievable.

The phenomenon of nitrogen leaching serves as a pertinent illustration of environmental consequences that are not completely eradicated. While several studies indicate a potential reduction in nitrate leaching when employing organic management practices, it is important to note that the resulting quantities of nitrate may still provide a risk of contributing to groundwater pollution. Pimentel and Burgess (2014) conducted a comparison of three different rotations that varied in terms of nitrogen sources. These rotations included an organic rotation that incorporated legume cover crops, an organic rotation that utilized animal manures, and a conventional rotation that relied on synthetic fertilizers. The researchers discovered that the leachate samples from all three treatments occasionally surpassed the regulation threshold of 10 ppm for nitrate concentration in potable water. According to Pimentel and Burgess (2014), the nitrogen given to the crops in the form of nitrate experienced a reduction of 20% in the organic animal rotation, 32% in the organic legume rotation, and 20% in the conventional rotation. The leaching of nitrogen from organic sources was found to be higher compared to that of conventional fertilizers. According to Valenzuela (2023), the application of manures and legume cover crops resulted in the highest nutrient release during periods of fallow or during times that did not align with the crop's nitrogen need.

While it is acknowledged that organic management can lead to an enhancement in soil quality compared to conventional management (Lin et al., 2023), it is important to note that the utilization of tillage for weed control and the incorporation of biomass from cover crops still pose hazards of soil loss and degradation (Francaviglia et al., 2023). The deleterious impacts of tillage, as demonstrated by Pearsons et al. (2023), encompass compaction, erosion, and a reduction in soil biological activity. According to the findings presented in the study conducted by Arnhold et al. (2014), research examining erosion rates in organic and conventional agricultural systems has yielded inconsistent outcomes, which can be attributed to factors such as the specific crop rotation, types of crops employed, and the methods of tillage employed. According to Arnhold et al. (2014), the study conducted by the authors in mountainous regions of Korea revealed that soil erosion rates, regardless of whether conventional or organic management practices were employed, were deemed excessive and unsustainable for long-term productivity. There has been a growing interest in the adoption of no-till techniques for organic farming due to the recognition of the advantages associated with minimizing tillage (Szczepanek et al., 2023). The typical procedure involves cultivating a cover crop before the primary cash crop, followed by mechanically crushing it and afterward planting through the resulting residue (Lamichhane et al., 2023). When executed accurately, the application of mulch effectively inhibits the growth of weeds, hence eliminating the necessity for cultivation in relation to the specific crop. Nevertheless, cultivating the requisite biomass in the cover crop to achieve efficient weed management might pose a formidable obstacle, and the feasibility of this approach may be constrained in arid regions where the cover crop competes for scarce water resources (Nosratti et al., 2023). Perennial weeds present a distinct challenge due to their inherent ability to penetrate and thrive within mulch layers (Ruch et al., 2023).

According to Gou et al. (2022), when considering the measurement of organic systems on a per-area basis, they may exhibit superior performance compared to conventional systems. However, it is important to account for the yield gap in organic systems, as this factor may contribute to higher emissions per unit of output. According to Jones et al. (2023), the rise in soil carbon levels in annual systems is accompanied by the emission of other gases, such as nitrous oxide, which counteract the potential benefits by contributing to climate change. The potential environmental ramifications of differences in yields between organic and conventional systems are also of significance. It is widely acknowledged in academic discourse that organic systems tend to exhibit lower productivity, typically resulting in a reduction in yield ranging from approximately 20% to 25%. However, scholarly literature indicates that this range can vary significantly, spanning from 5% to 50%, contingent upon factors such as the specific crop, soil conditions, level of management intensity, and the methodologies employed in the respective studies (Prairie et al., 2023; Santoni et al., 2023). Critics contend that the implementation of organic management practices would necessitate the allocation of additional land for agricultural purposes to ensure the sustenance of global food security. The consequences of this action would include deforestation and the subsequent loss of habitats, resulting in an adverse environmental outcome (Wijerathna-Yapa & Pathirana, 2022; Raihan & Tuspekova, 2022b). In light of the aforementioned issues inherent in the ongoing discourse between organic and conventional approaches, it appears prudent to explore alternative methodologies and strategies that could potentially offer viable resolutions. Rather than adopting a binary perspective when considering our agricultural landscapes, it may be more advantageous to embrace a mindset that incorporates both options, sometimes referred to as a "yes-and" approach. Numerous scholars have advocated for the use of a multidisciplinary and multifunctional framework in the design of agroecosystems, as evidenced by the works of Taylor and Lovell (2021), Thiesen et al. (2022), and Stokes et al. (2023). When considering the challenge of simultaneously providing sustenance to the global population and ensuring the long-term viability of the planet, Foley aptly asserts that a singular approach is inadequate for addressing all the associated issues. Consider the utilization of silver buckshot rather than relying solely on a silver bullet.

Agroforestry Systems

Agroforestry is a multifunctional method that involves the deliberate integration of trees and shrubs with crops or livestock within our food system. The sustainable agricultural technique of agroforestry has been acknowledged for around 50 years (Aryal et al., 2023). The integration of trees into the agricultural landscape is a concept that has existed since the inception of land cultivation. Agroforestry has been found to yield several advantageous results. These include the mitigation of nutrient and pesticide runoff, the sequestration of carbon, the enhancement of soil quality, the control of erosion, the improvement of wildlife habitat, the reduction of fossil fuel consumption, and the promotion of resilience in the context of an unpredictable agricultural future (Sollen-Norrlin et al., 2020; Temegne et al., 2021; Jinger et al., 2022). In summary, the incorporation of trees and other perennial vegetation into a landscape has the potential to alleviate the adverse impacts associated with agricultural practices. Agroforestry exhibits significant potential as a land use plan in both developed and developing regions due to its capacity to concurrently deliver economic, ecological, and cultural advantages (Telwala, 2023; Viñals et al., 2023). Furthermore, agroforestry has the capacity to provide a wide range of goods including timber, crops, fruits, nuts, mushrooms, forages, cattle, biomass, Christmas trees, and herbal medicine (Sollen-Norrlin et al., 2020). A comprehensive assortment of products in a portfolio would facilitate the distribution of revenue streams over different time horizons. These items encompass short-term options such as crops, pasture, livestock, mushrooms, and certain fruits like currants. Additionally, medium-term possibilities include nuts, fruits such as apples or persimmons, biomass, and medicinal plants. Lastly, long-term prospects involve lumber and the potential for increasing property value. The presence of a wide range of products can potentially mitigate risks for farmers while necessitating innovative marketing strategies (Jacquet et al., 2022; Raihan & Tuspekova, 2022c).

Various forms of agroforestry are implemented in different regions worldwide. The field of tropical agroforestry has historically received greater attention and has been more extensively implemented compared to temperate agroforestry. According to Piato et al. (2021), shade-grown coffee and tea systems have undergone significant advancements, and the presence of manual labor renders some tropical agroforestry approaches more feasible compared to regions where mechanized harvesting is prevalent. Agroforestry has held significant cultural significance in indigenous tropical regions as well as temperate locales such as Europe. However, the prevalence of land abandonment and agricultural intensification in northern territories has resulted in a reduction of conventional agroforestry methods (Nair et al., 2021). There exist five widely acknowledged agroforestry approaches, including alley cropping, silvopasture, riparian buffers, windbreaks, and forest farming (Bishaw et al., 2022). These approaches are applicable across diverse farming systems, topographical features, and climatic regions. Figure 4 illustrates various agroforestry approaches.

Alley cropping

Alley cropping is a sustainable agricultural practice that entails cultivating row crops within the spaces between rows of trees (Gagliardi et al., 2022). Trees have the potential to be cultivated for the purpose of producing lumber or fruits and nuts. On the other hand, alley crops encompass a diverse range of cereals, vegetables, or forages that can be harvested for hay. The cultivation of crops yields immediate financial returns, whereas the growth of trees generates money over an extended period of time.

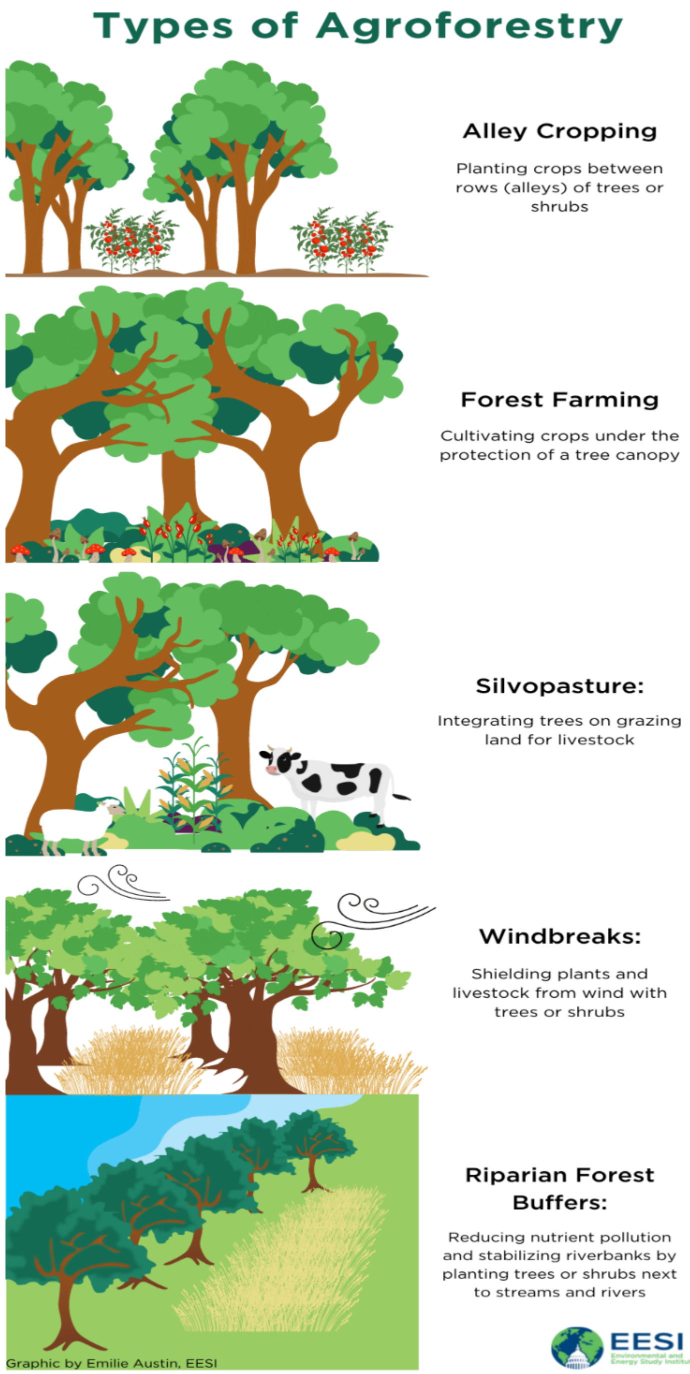

Figure 4. Different types of agroforestry practices.

The potential for enhanced production can arise from the interactions between tree and crop species, facilitated by their distinct ecological niches (Fahad et al., 2022). An illustrative instance can be found in a study conducted in France, which demonstrated the favorable compatibility between walnuts and winter wheat due to their distinct growth periods and divergent rooting depths. According to the findings of Dupraz et al. (2021), it was determined that the integrated cultivation technique yields a 40% higher product output per unit area compared to the separate cultivation of the two crops.

Forest farming

Forest farming encompasses a range of activities, including the cultivation of mushrooms, the collection of medicinal herbs such as ginseng and goldenseal, and the commercialization of woody ornamental resources (Chamberlain et al., 2019). The agroforestry method described in this study typically takes place within mature forests that have been cultivated for lumber production, enabling the generation of income without significant disruption (Frey et al., 2023). The management of forest farming systems can vary in intensity, with the level of management determined by the specific product being cultivated and the target market preferences (Raihan & Tuspekova, 2022d). As an illustration, the cultivation of ginseng in woodland environments necessitates substantial pre-planting measures such as site preparation, application of fertilizers, tillage practices, and the use of fungicides. While these interventions have the potential to enhance crop yields, they also incur higher costs and thus introduce greater financial and operational uncertainties. In contrast, the cultivation of wild-simulated ginseng may encompass the practice of gently displacing fallen foliage, sowing seeds, and allowing the ginseng to mature over a span of multiple years prior to its eventual harvest (Yousefi et al., 2020).

Silvopasture

The practice of silvopasture involves the deliberate integration of cattle within a carefully planned combination of trees and pastureland. Silvopasture distinguishes itself from conventional woodland grazing practices by implementing a deliberate arrangement of trees that ensures adequate sunlight penetration for the underlying fodder vegetation, while simultaneously preventing any detrimental impact on the trees caused by animals. According to Smith et al. (2022), the presence of trees provides animals with shelter by offering shade during the hot summer months and reducing wind exposure during the cold winter season. Furthermore, it has been observed that the quality of pasture in areas with partial shade may exhibit an improvement, but with a minor decrease in biomass productivity (Hidalgo-Galvez et al., 2022). According to Poudel et al. (2022), there is no significant difference in the weight gains of livestock when comparing silvopasture with open pasture grazing systems. According to Huang et al. (2023), if the trees are cultivated for lumber purposes as well, it is expected that the farmer's long-term financial performance will enhance without compromising the current level of production.

Windbreaks

Windbreaks, sometimes referred to as shelterbelts, were promptly acknowledged as a valuable agroforestry technique. Windbreaks play a crucial role in mitigating wind erosion, supporting wildlife habitats, and enhancing water availability for adjacent crops through reduced evapotranspiration and snow capture effects (Subbulakshmi et al., 2023). According to Mallareddy et al. (2023), an increased water supply has the potential to enhance agricultural productivity, hence yielding significant economic advantages for farmers. Windbreaks have the potential to mitigate the heating and cooling requirements of residential and occupational areas on a farmstead by minimizing the infiltration of outdoor air induced by wind (Mume & Workalemahu, 2021). The initiation of the Prairie States Forestry Project by the U.S. government was a response to the Dust Bowl years in North America, aiming to establish a substantial shelterbelt spanning from Canada to Texas (Li, 2021). Another noteworthy illustration pertains to the Three-North Shelter Forest Program in China, which stands as the most extensive afforestation endeavor globally. The initiative commonly referred to as "China's Great Green Wall" was initiated in 1978 and is projected to reach completion by 2050 (Gravesen & Funder, 2022). Comparable approaches have been utilized in Russia, the northern regions of Europe, Australia, New Zealand, and many other nations.

Riparian forest buffers

Riparian buffers refer to vegetated zones established along watercourses that are susceptible to erosion, nutrient leaching, or habitat degradation (Fahad et al., 2022). Typically, there exist two to three distinct "zones" of vegetation, which exhibit variations in their composition as influenced by factors such as proximity to the waterway, slope, and the requirements of primary producers (Lind et al., 2019). Riparian zones have limited suitability for agricultural production, rendering them highly suitable for alternate utilization. The United States Department of Agriculture (USDA) has made a deliberate and coordinated endeavor to enforce conservation practices in the vicinity of water bodies, owing to their advantageous effects on the quality of water and soil. The Environmental Quality Incentive Program (EQIP), administered by the Natural Resources Conservation Service (NRCS), and the Conservation Reserve Program (CRP), managed by the Farm Service Agency (FSA), serve as illustrations of government-funded efforts.

It is important to highlight that, among the five practices mentioned, alley cropping and silvopasture are commonly implemented on land that is deemed appropriate for conventional agriculture. Despite this, it is common practice to engage in conventional cropping for multiple years until the trees reach their full maturity (Dasgupta et al., 2023). Riparian buffers, windbreaks, and forest farming typically manifest in the periphery of fields or on land that is unsuitable for agricultural use. However, it is worth mentioning that in certain instances, the allocation of a portion of cropland may be necessary to achieve the desired width for optimal efficacy (Englund et al., 2021). Hence, these methods have a tendency to serve as a supplement rather than a rival to current production systems, perhaps offering avenues to enhance food security through the utilization of underutilized resources. Agroforestry has the potential to make significant contributions to both conventional and organic agricultural systems in practical applications. In both scenarios, the advantageous impacts of agroforestry have the potential to enhance environmental results beyond the existing capabilities of each respective system. Agroforestry has the potential to mitigate several of the aforementioned issues associated with organic agriculture, such as soil erosion, emissions of greenhouse gases, and leaching of nutrients.

Agroforestry Benefits

The practice of agroforestry has been found to have beneficial impacts on both soil and water quality. The enhancement of soil quality is facilitated by heightened amounts of organic matter, greater diversity in microbial populations, and enhanced nutrient cycling, hence potentially augmenting crop output and bolstering resilience against drought conditions (Fahad et al., 2022). The incorporation of agroforestry vegetative buffer strips has been found to reduce non-point source pollution from row crops, resulting in improvements in water quality (Zahoor & Mushtaq, 2023). Fahad et al. (2022) observed that the implementation of agroforestry and grass buffer strips had a significant impact on reducing the loss of phosphate and nitrogen from a corn-soybean cycle. Perennial vegetation exhibits the capacity to enhance above-ground biomass, thereby impeding runoff and effectively capturing up to 95% of susceptible sediment from being lost (Liu & Lobb, 2021). Additionally, the subterranean roots of these plants have the ability to absorb 80% or more of surplus nutrients, while concurrently serving as a habitat for microbial communities capable of metabolizing pesticides (Behera et al., 2021).

The augmentation of soil organic matter through carbon content not only enhances soil health but also contributes to the mitigation of atmospheric carbon dioxide, which is recognized as a significant factor in climate change (Paul et al., 2023; Raihan et al., 2022a; Raihan & Tuspekova, 2022e; Raihan & Tuspekova, 2023a). According to Lugo-Pérez et al. (2023), the inclusion of trees and shrubs in an agricultural landscape results in a higher degree of carbon sequestration when compared to a monoculture of crops or grassland. In a study conducted by Kim et al. (2016), a meta-analysis was performed to assess the impact of agroforestry on greenhouse gas emissions. The findings of the study revealed a significant reduction in emissions, with an average mitigation rate of 27±14 tons of CO_2 per hectare per year. Approximately 70% of carbon sequestration was attributed to biomass, while the remaining 30% was sequestered in the soil. According to a study conducted by Udawatta and Jose (2011) in North America, the implementation of agroforestry methods on a small scale has the potential to store around 548.4 Tg of carbon annually. This amount is significant enough to offset almost 34% of the carbon emissions produced by the United States from the burning of coal, oil, and gas. The strategies for enhancing carbon sequestration encompass improved erosion management, heightened carbon storage in woody perennial plants, diminished decomposition of organic matter, and the limited harvesting of crop biomass in agroforestry systems compared to conventional systems (Sivaranjani & Panwar, 2023). The potential significance of the relationship between perennial systems and climate change should not be overlooked. The study conducted by Robertson et al. (2020) examined the possible impact of various annual and perennial systems on global warming. The research findings indicate that all of the annual cropping systems examined, including conventional, no-till, reduced input, and organic, did not result in a reduction of global warming potential. While the farming techniques did indeed result in the accumulation of carbon in the soil, the benefits derived from this were counteracted by the emissions of nitrous oxide. Nevertheless, the implementation of perennial and early successional forest treatments, such as the utilization of alfalfa, hybrid poplar, and the restoration of abandoned early successional sites, resulted in a notable decrease in global warming potential. As the mid-successional and late-successional systems progressed in their development, the annual carbon storage capacity exhibited a decline. The study's findings indicated that the early successional forest system emerged as the most effective strategy for mitigation (Raihan & Tuspekova, 2022f; Raihan & Tuspekova, 2023b). Numerous agroforestry practices demonstrate a high degree of resemblance to the characteristics and dynamics of early successional forests.

The mitigation of climate change is furthered by the adoption of an additional significant strategy, namely the reduction of fossil fuel consumption (Raihan & Tuspekova, 2022g; Raihan et al., 2023b; Raihan, 2023h; Raihan, 2024b). The utilization of bioenergy presents a potential solution for mitigating reliance on fossil fuels (Raihan, 2023i; 2023j). However, apprehensions arise regarding the allocation of important arable land for cultivating energy crops instead of food crops (Kalogiannidis et al., 2023). At present, a significant proportion of the corn yield in the United States, specifically 40%, is allocated towards the production of ethanol. This allocation raises concerns over its potential counterproductivity in relation to the overarching objective of alleviating global food scarcity. According to Ntawuruhunga et al. (2023), the integration of biomass production from trees and food cultivation on the same site holds potential as an agroforestry approach to provide a sustainable energy future without compromising food production capacities. The Land Equivalent Ratio (LER) is a valuable metric for evaluating the comparison between polycultures, which consist of mixed species, and individual crops. This metric takes into account the productivity of the polyculture and computes the land area that would be necessary if the individual crops were cultivated independently. In a study conducted by Haile et al. (2016), a comparison was made between loblolly pine and switchgrass mixes and pure stands of each crop. The researchers observed that while the individual crop yields were lower in the mix, the overall Land Equivalent Ratio (LER) reached 1.47. This implies that cultivating switchgrass and loblolly pine individually would necessitate an additional 47% of land compared to the agroforestry system in order to produce an equivalent quantity of biomass. The Yield-SAFE (Yield Estimator for Long-term Design of Silvoarable Agroforestry in Europe) model was employed to simulate agroforestry systems in Europe. The results of this modeling exercise indicated that integrating trees and crops in Spain, France, and the Netherlands led to higher productivity, as evidenced by the predicted LER (Land Equivalent Ratio) values ranging from 1 to 1.4. This finding was reported by Graves et al. (2007). In a separate study conducted in Switzerland, the implementation of agroforestry models centered around walnut (Juglans hybrid) and wild cherry showed that, in 12 out of 14 instances, the integration of multiple crops resulted in a higher Land Equivalent Ratio (LER) above unity. Furthermore, Sereke et al. (2015) revealed that a significant majority, specifically 68%, of the financial scenarios in Switzerland exhibited higher profitability compared to existing methods.

Agroforestry demonstrates a greater capacity for biodiversity conservation in comparison to conventional and organic monocultures. The inclusion of trees, bushes, and other permanent vegetation within an agricultural landscape has been found to enhance wildlife habitat, resulting in increased abundance and higher diversity of wildlife populations (Ntawuruhunga et al., 2023). In addition to possessing inherent worth, biodiversity has the potential to offer valuable services. According to Ghosh et al. (2023), an increased presence of avian species and predatory insects can effectively regulate pest populations. The provision of suitable habitats for pollinator species has been found to positively impact the pollination of horticulture crops, as demonstrated by Miñarro et al. (2023). According to Ribas et al. (2023), there is typically a decline in the occurrence of diseases in populations that exhibit higher levels of diversity, encompassing both plant and wildlife species. Agroforestry can also provide advantages for livestock. According to Smith et al. (2022), windbreaks serve as a protective barrier against strong winds, safeguarding animals from their adverse effects. Additionally, the provision of shade by trees can enhance thermal comfort during the summer season, potentially promoting more uniform grazing patterns across a paddock. According to Kumar et al. (2023), the implementation of forest-based foraging systems for poultry and hogs has the potential to reduce reliance on grain and create environments that closely resemble the natural habitats of these animals. The cork oak dehesas found in the Mediterranean region exemplify a multifunctional landscape that has persisted for several centuries. These landscapes serve as a source of sustenance for grazing cattle through the provision of grass and acorns, while also offering a lucrative cash crop in the form of bark that is utilized in the production of traditional corks (Acha & Newing, 2015).

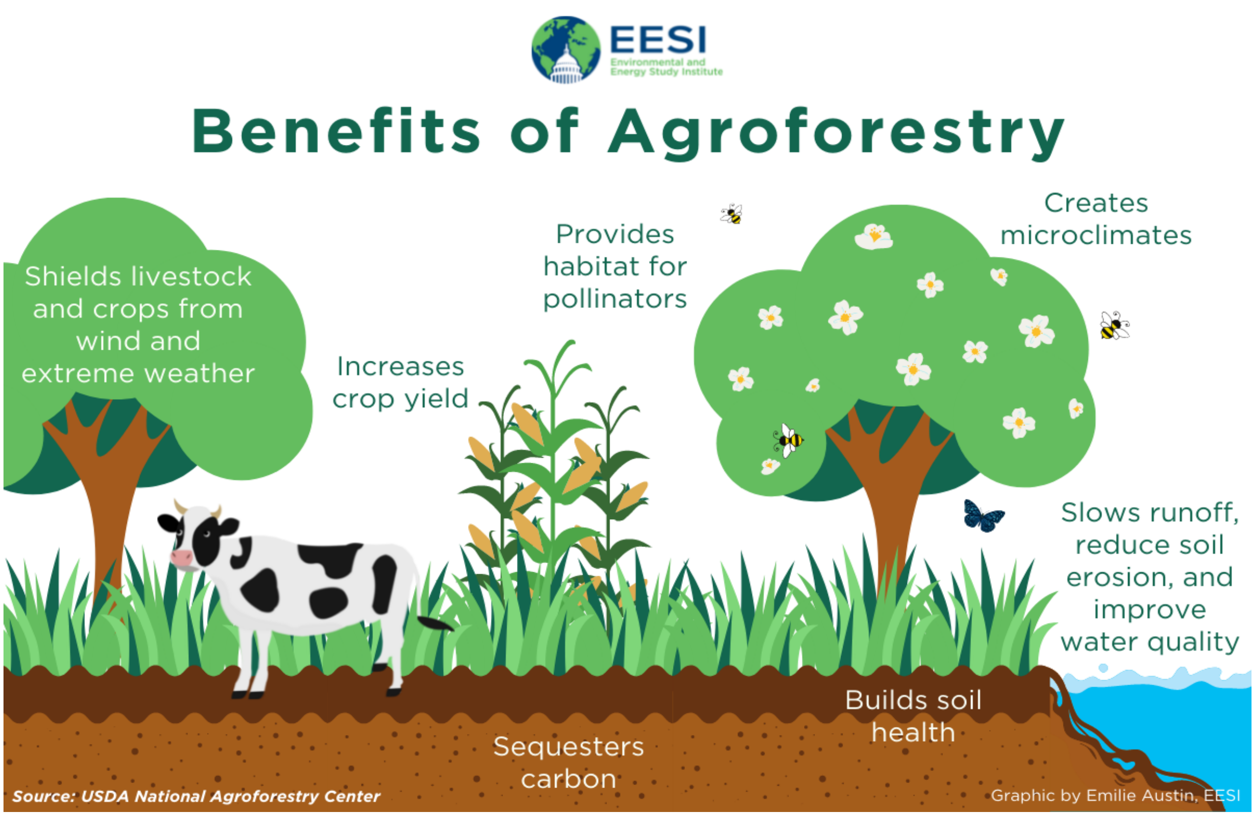

Figure 5. The benefits of agroforestry.

According to Chenyang et al. (2021), perennial polycultures such as agroforestry exhibit more intrinsic stability when confronted with global market volatility and extreme climatic events, in comparison to annual monocultures. In the hypothetical scenario of a scarcity of fossil fuels, it is anticipated that mature fruit and nut trees will sustain their production with minimal disruption, albeit necessitating the substitution of labor for alternative inputs. Agroforests possess the capacity to store greenhouse gases, which are recognized as the primary drivers of global climate change (Wilson & Lovell, 2016; Raihan et al., 2022b; Jubair et al., 2023; Raihan, 2024c). Additionally, these agroforests have a heightened ability to withstand and adapt to the anticipated impacts of climate change. According to Rajanna et al. (2023), enhanced root systems and increased capacity for infiltration and water retention contribute to mitigating the effects of drought. Additionally, trees exhibit superior resilience to floods compared to field crops due to their capacity to extract surplus water from the soil and endure inundation. Despite being frequently disregarded, agroforestry offers supplementary cultural advantages. The preservation of nature is highly esteemed by several landowners due to its aesthetic appeal and perceived advantages, such as enhanced well-being and the tranquility associated with rural living (Tindale et al., 2023). According to a study conducted by Jiang et al. (2023), rural dwellers exhibit a preference for aesthetics that are enhanced by the use of measures such as vegetative buffers. Etongo et al. (2023) highlight several recreational activities available, such as bird watching, outdoor excursions, and hunting. The benefits of agroforestry are illustrated in Figure 5.

Agroforestry Adoption Challenges and Future Directions to Overcome

The prospects for agroforestry are promising, albeit not devoid of obstacles. The adoption of agroforestry has exhibited a notable deficiency, despite the existence of extensively demonstrated advantages (Syano et al., 2022). Various obstacles have been identified, such as the financial burden associated with setting up tree plantations, landowners' limited familiarity with tree cultivation, and the considerable time and expertise necessary for effective management (Irwin et al., 2023). According to Wienhold and Goulao (2023), extension employees and agricultural product merchants are commonly relied upon by farmers for acquiring knowledge about novel agricultural methods. However, it is worth noting that these experts generally lack formal training or practical expertise in the field of agroforestry. Furthermore, the absence of well-defined demonstration plots poses a challenge for landowners in observing the practical implementation of these systems (Zang et al., 2022). Given the intangible or long-term nature of numerous beneficial outcomes associated with agroforestry, landowners may encounter challenges in visualizing them (Jacobs et al., 2023).

The logistics associated with the harvest of edible goods, such as fruits and nuts, in agroforestry systems can pose significant challenges. In order to enhance the economic competitiveness of agroforestry systems, the implementation of mechanization may be necessary for larger-scale plantings (Korneeva & Belyaev, 2022). The complexity of the situation arises when numerous types of fruit or nut are cultivated simultaneously. According to Irwin et al. (2023), non-traditional markets and delayed rewards can also serve as deterrents. Previous studies have demonstrated that certain agroforestry systems, like silvopasture, exhibit economic viability and generate profits. However, other practices such as biomass plantings or riparian buffers may require the establishment of markets that provide compensation for the ecosystem services, they offer in order to be financially feasible (Mosquera-Losada et al., 2023; Ntawuruhunga et al., 2023). Additionally, the process of social change and networking will also be influential as attitudes shift to embrace alternative approaches (Annosi et al., 2022).

In light of the aforementioned obstacles, several techniques have been presented with the aim of advancing the field of agroforestry. Potential policy adjustments may involve the augmentation of financial resources allocated towards government cost-sharing initiatives aimed at facilitating the implementation of sustainable practices. Additionally, the provision of incentives, such as credits, for the provision of environmental services, including but not limited to pollination and carbon sequestration, might be considered. The existing programs offered by the United States Department of Agriculture (USDA) through the Natural Resources Conservation Service (NRCS) and the Farm Service Agency (FSA) frequently include provisions that prohibit the harvesting of land designated for conservation purposes. However, the implementation of agroforestry systems has the potential to allow for the cultivation of harvestable products while still maintaining the conservation objectives. The implementation of a policy modification that permits the non-destructive extraction of consumable products from agroforestry systems could potentially incentivize a greater number of farmers to embrace agroforestry methods, hence resulting in improved conservation outcomes. While it is justifiable that a significant portion of government financing is allocated to support prominent cropping systems like maize and soybean, it is worth considering that agroforestry possesses the potential to mitigate the adverse impacts associated with these systems. Consequently, it is advisable to allocate greater attention and resources to agroforestry practices. A portion of this assistance has the potential to be allocated towards educational initiatives, specifically through the implementation of extension and university programs. Indeed, education emerges as a critical determinant for the adoption of conservation techniques, since numerous research investigating the adoption phenomenon consistently identify limited access to knowledge and technical support as a prominent obstacle.

The potential for expanding the output capacity of agroforestry systems remains largely untapped. Further investigation is required to examine the utilization of trees and shrubs in the production of commercially viable goods. In recent times, there has been a surge in interest in the advancement of multifunctional, consumable polycultures that emulate natural ecosystems, such as the indigenous oak savannas found in the Midwest region. These polycultures encompass the cultivation of various crops in a stacked arrangement, enabling the utilization of diverse ecological niches and the generation of multiple revenue streams. Field trials were conducted at the University of Illinois at Champaign-Urbana to investigate the cultivation of a combination of chestnuts, hazelnuts, apples, currants, and raspberries. The inclusion of control plots in a conventionally managed corn and soy rotation enables the opportunity to conduct a comprehensive examination of various environmental, ecological, and economic variables for comparison purposes. A comprehensive and repeatable investigation was conducted to examine various spatial arrangements of polycultures in comparison to monocultures of individual species, as they would typically be cultivated in a commercial orchard setting. Additionally, the study allowed for a comparison between these polycultures and a corn/soybean rotation. The treatments encompass the incorporation of indigenous trees and shrubs that possess consumable produce, such as aronia, elderberry, pecan, pawpaw, persimmon, plum, and serviceberry. This study investigates the potential scope of cultivating native culinary plants within conservation easements that require the exclusive utilization of indigenous species.

Conclusion

This paper aims to provide a review of agroforestry toward sustainable and resilient agriculture for the future world. Numerous strategies have been suggested to effectively and durably address the challenge of providing nourishment to an expanding global populace. Organic farming exhibits the potential to reduce the reliance on agrichemicals and enhance specific environmental and human health indicators. Conversely, advocates of conventional farming systems highlight the benefits associated with the utilization of genetic engineering, fertilizers, and pest control methods to enhance crop productivity. The implementation of broader methods encompasses various approaches, such as the restriction of farmland expansion through the prevention of deforestation, the reduction of food waste, the adoption of a less meat-intensive diet, the closure of yield gaps in underperforming cropland within emerging nations, and the enhancement of resource efficiency pertaining to water, fertilizer, and fuel utilization. These aforementioned endeavors, together with additional strategies, will be imperative components of a comprehensive approach in order to effectively and enduringly address global food security.

The natural environment yields its abundance without necessitating the use of plowing, fertilizers, or pest control measures, hence obviating the need for any external inputs. The system operates only on solar energy and does not produce any detrimental waste byproducts. The presence of biological diversity enables the capacity for dynamic adaptation in response to environmental changes. By emulating the operation of natural ecosystems, agricultural systems have the potential to enhance their stability and resilience. Constructing such a system undoubtedly presents a formidable undertaking, necessitating a diverse array of technologies. Agroforestry has the potential to serve as a progressive approach in the realm of sustainable agriculture. It achieves this by advocating for and implementing integrated and biodiverse practices that aim to enhance crop yields, mitigate adverse impacts, and deepen our comprehension of the intricate interdependencies inherent in augmenting food production while mitigating harm. Agroforestry could lead to long-term sustainable change with a balance between short-term economic benefits and long-term sustainability goals. Sustainable agroforestry systems have the potential to help farmers harness the interactions occurring between the different components of the system for a multitude of benefits such as increased yield, environmental benefits, and animal welfare. Therefore, agroforestry should be given higher priority as a nature-based solution in policies and programs aimed at ecosystem restoration, land degradation neutrality, and climate change mitigation goals, particularly for developing countries.

Declaration

Acknowledgment: N/A

Funding: This research received no funding.

Conflict of interest: The author declares no conflict of interest.

Authors contribution: Asif Raihan contributed to conceptualization, visualization, methodology, reviewing literature, extracting information, synthesizing, and manuscript writing.

Data availability: The author confirms that the data supporting the findings of this study are available within the article.

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