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Agroecological approaches to sustainable development

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Agroecology has emerged as a fundamental paradigm for developing innovative solutions to major global concerns such as food security, biodiversity loss, and climate change. The core subject of biodiversity conservation emphasizes agroecology's role in the preservation of native species, pollinators, and beneficial creatures through practices such as agroforestry, cover crops, and decreased chemical inputs. Agroecological principles such as polyculture, crop diversity, and integrated pest control help to improve food security by increasing stability and nutrition. Agroecology encourages carbon sequestration, soil health, and greenhouse gas reductions, resulting in climate-resilient farming systems. The literature review revealed that no article thoroughly discusses all of the critical hitting global challenges, such as food security, biodiversity loss, and climate change, in a single study that can be addressed using agroecological principles. This review article attempts to make a connection between numerous challenges that may be solved using agroecological techniques in order to facilitate sustainable growth while protecting the environment. The study examines the benefits of incorporating agroecological methodologies into sustainable agriculture, with an emphasis on increasing agroecosystem resilience, improving socioeconomic circumstances for smallholder farmers, rural livelihoods, and local communities, and contributing to climate change mitigation. It provides a complete review of agroecological concepts and their numerous advantages, making it an excellent guide for policymakers, academics, and practitioners who is working to build a sustainable and resilient global food system. Agroecology emerges as a light of hope, boosting agricultural output while also protecting the environment, with the ultimate goal of achieving harmonious cohabitation between mankind and the natural world.

KEYWORDS

agroecology, biodiversity, climate change, food security, sustainable development

Introduction

Agroecology integrates ecological principles into agriculture for sustainability. It promotes biodiversity, crop rotation, soil health, and natural pest control (Yadav et al., 2021). Agroforestry and local knowledge are valued (Saliu et al., 2023). This approach enhances food security, conserves biodiversity, mitigates climate change, and reduces environmental impact (Patel et al., 2020). Resilient farming systems and social equity are key components, supporting communities and traditions (Reyes et al., 2020). Agroecology offers a solution for sustainable agriculture, addressing food security, biodiversity loss, and climate change while prioritizing ecosystem and human well-being (De La Riva et al., 2023).

Major global challenges are interwoven with the security of our fundamental resources: food and water. Climate change and global warming disrupt weather patterns, resulting in extreme events that threaten agricultural productivity and amplify the vulnerability of already precarious food systems (Tofu et al., 2022). Biodiversity loss compounds these issues, as shrinking ecosystems undermine the resilience of ecosystems essential for pollination, soil

health, and disease control. Moreover, agrochemicals, although intended to boost yields, can inadvertently harm ecosystems and human health, highlighting the demand for more environmentally friendly farming methods (World Health Organization, 2021). In order to solve these issues and guarantee the security of food and water, as well as the intricate interactions among human activity, the environment, and the delicate balance of nature, swift action is needed (Mishra et al., 2021).

Agroecological practices play a pivotal role in mitigating the impacts of climate change. Strategies such as carbon sequestration in soils, reduced dependence on synthetic fertilizers and pesticides, and the implementation of agroforestry systems collectively contribute to the reduction of greenhouse gas emissions (Muhie, 2022). Additionally, the diversified cropping systems fostered by agroecology enhance soil health and augment resilience against climate-induced stresses (Amede et al., 2023). Amid the concerning biodiversity loss, agroecology emerges as a beacon of hope. By advocating for diverse crop varieties, the establishment of mixed farming systems, and the preservation of habitats, agroecology actively promotes biodiversity (Calo et al., 2023). The reduction in chemical inputs and the promotion of natural pest control mechanisms not only enhance ecosystem health but also significantly contribute to the conservation of global biodiversity (Kremen, 2020).

In the realm of food security, agroecological practices play a vital role in ensuring sustainable nourishment. By bolstering soil fertility, encouraging crop diversity, and supporting local food production, agroecology acts as a buffer against the challenges posed by a changing climate (McLennon et al., 2021; Madsen et al., 2021). The emphasis on sustainable practices equips communities to adapt to evolving environmental conditions and ensures consistent access to wholesome food. Water scarcity, a growing concern, finds a potential ally in agroecology (Nabhan et al., 2020). The adoption of practices like rainwater harvesting, drip irrigation, and soil conservation techniques enables efficient water management. The improvement of soil structure and water retention capacities within agroecological systems not only curtails water demand but also maintains agricultural productivity (Odhambo et al., 2021; Roohi et al., 2022). In addressing health pandemics, agroecology champions local and diversified food systems. By circumventing the reliance on intricate global supply chains, the spread of diseases can be mitigated. Moreover, the promotion of robust ecosystems through agroecological practices offers a shield against disease transmission risks (Barrett et al., 2020).

Agroecology's impact on poverty reduction and inequality is profound (Kroll, 2021). By empowering small-scale farmers with knowledge and tools, agroecology diversifies income sources and promotes equitable opportunities. This translates into a tangible upliftment of livelihoods and the creation of a more inclusive society. Agroecology's contribution to mitigating environmental degradation is of paramount importance. It decreases chemical pollution, prevents soil erosion, and promotes soil health through sustainable land management techniques (Anderson et al., 2022). The fight against environmental degradation that agroecology undertakes is characterised by the protection of ecosystems and the promotion of regenerative agriculture (Wojtynia et al., 2021).

Agroecology is a holistic approach (Figure 1) that tackles multiple global issues at once. Its emphasis on biodiversity, ecological sustainability, strengthening local communities, and developing

resilient agricultural systems has the potential to bring back a harmonious relationship between humans and the environment (Chable et al., 2020). The shift towards holistic, locally suited farming practices forms the pivotal foundation of agroecology's transformative contribution toward creating a world that is both more sustainable and equitable.

Agroecology and food security

Agroecology significantly contributes to food security by promoting diverse food production through a wide array of crops and livestock, mitigating risks associated with single crop failures and disease outbreaks, thus ensuring a consistent food supply. It emphasizes localized, small-scale farming systems, reducing dependency on distant food sources and minimizing transportation-related losses (Figure 2). Furthermore, the ability of agroecological systems to adapt improves their resilience against climatic variability, strengthening their ability to endure catastrophic weather events and guaranteeing a consistent supply of food (Kyriakopoulos and Sebos, 2023; Karandish et al., 2021).

Role of agroecological practices in ensuring stable food production

Stable food production, denoting the consistent and dependable generation of food resources to fulfill the nutritional requirements of a populace, is fundamental for upholding food security, defined as the ample accessibility and attainment of adequate quantity and quality of food for all members of a society (Ayinde et al., 2020). Agroecological methodologies serve as a cornerstone in ensuring stable food production by fostering resilient, sustainable, and diversified agricultural systems. These practices engender stability through various mechanisms: Diversification mitigates vulnerability by advocating for a wide array of crops and livestock species, thus offsetting the impact of crop failures (Carlile and Garnett, 2021). Adaptive management encourages farmers to tailor their practices to local ecosystems, ensuring continued production amidst changing conditions (Sinclair et al., 2019). Resilience to climate change is bolstered through biodiversity, resource management, and ecological equilibrium, rendering agroecological systems more adept at withstanding environmental fluctuations (Jhariya et al., 2021; Solankey et al., 2021). Natural pest management techniques circumvent the pitfalls of chemical reliance, averting pest resistance and fostering long-term crop stability (Deguine et al., 2021). Soil health and fertility are upheld via techniques like cover cropping and crop rotation, providing a sturdy foundation for consistent yields (McLennon et al., 2021). Reduced input dependency insulates farmers from price fluctuations, stabilizing production costs and food prices (Bonnet et al., 2021). Localized production diminishes reliance on distant sources, curbing supply chain disruptions and ensuring stability within local communities (Grilli et al., 2023). Furthermore, the preservation of traditional knowledge integrated into agroecological practices harnesses generations of wisdom, contributing to stable production under diverse conditions (Einbinder et al., 2022).

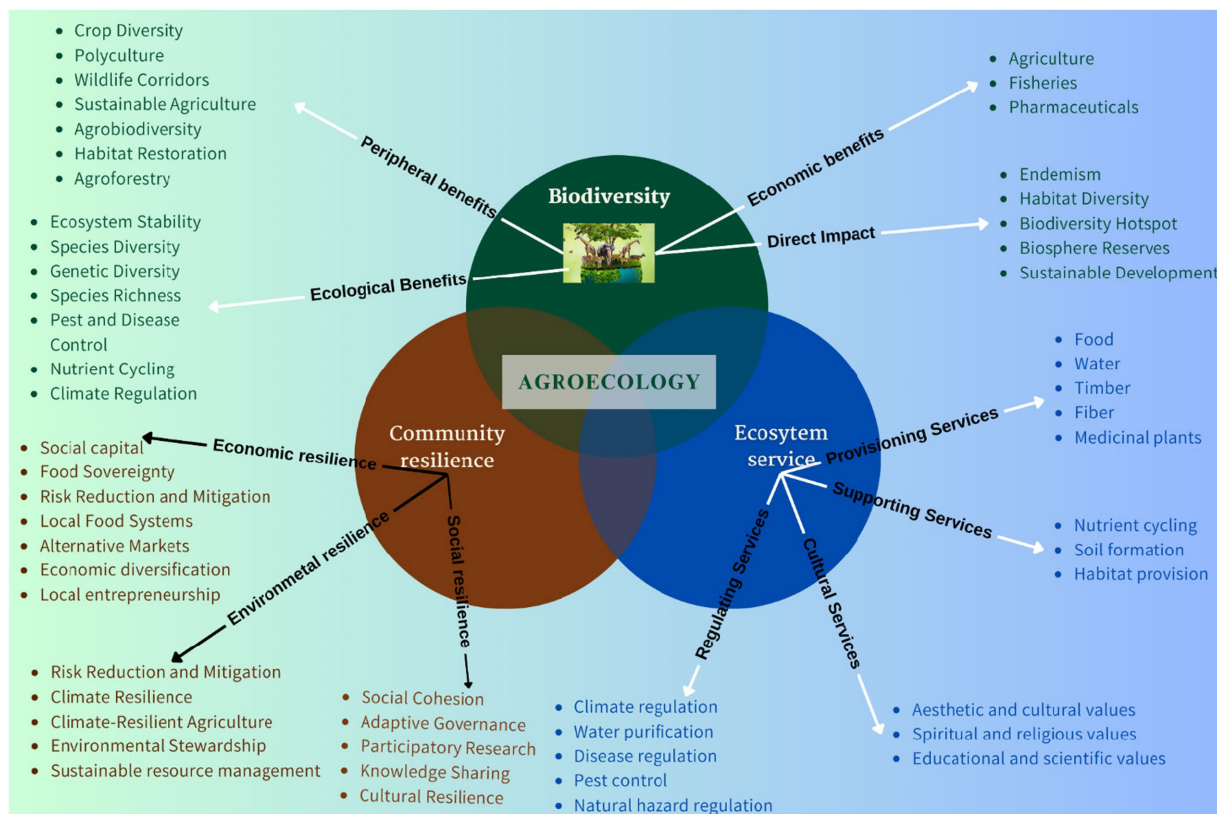


FIGURE 1 Agroecology’s multifaceted contribution to biodiversity and sustainable development. This figure illustrates how agroecology, as a holistic agricultural approach, interconnects with various components to foster biodiversity, community resilience.

Crop diversification, polyculture, and integrated pest management for enhanced yield stability

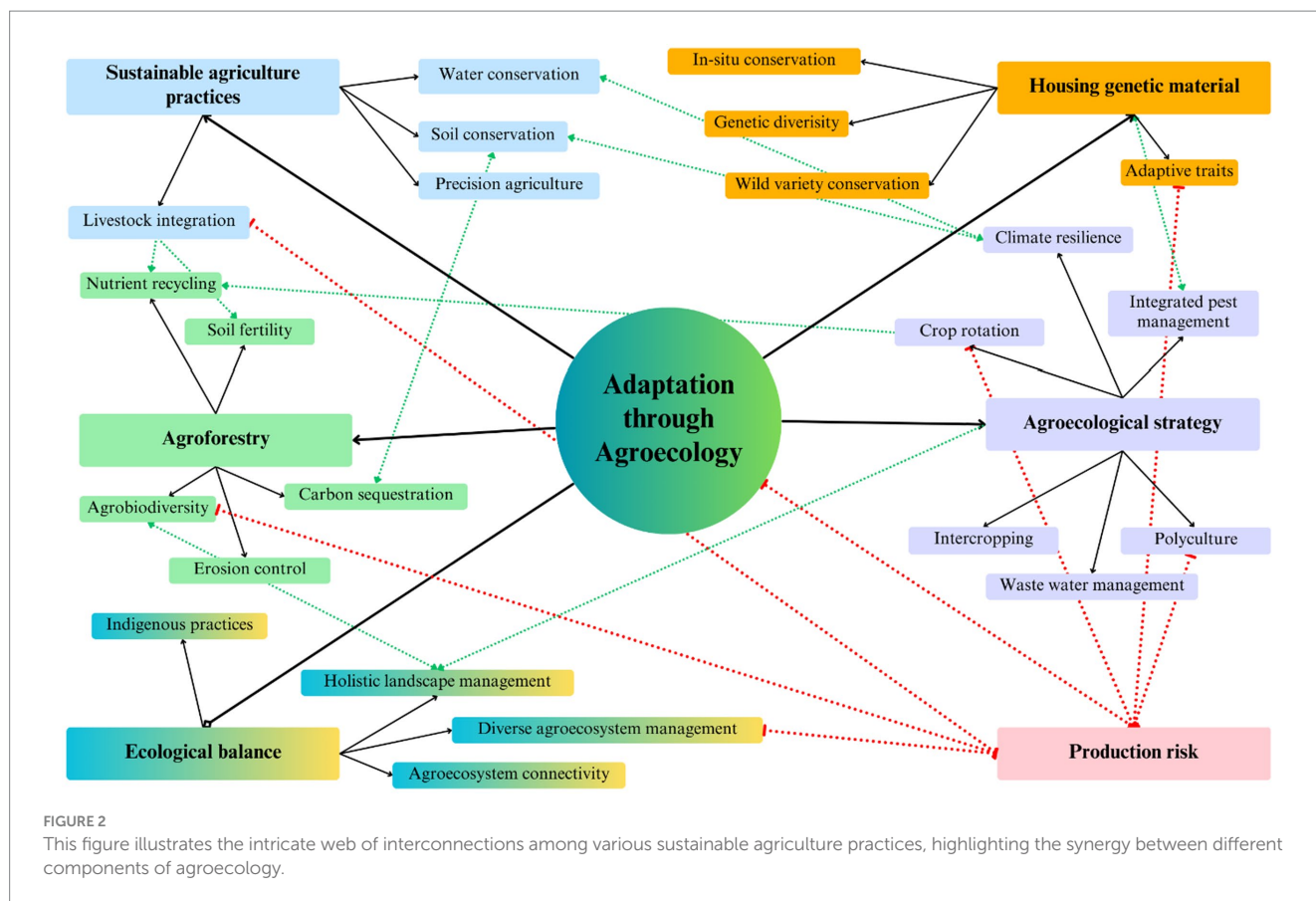
- i Crop diversification: Crop diversification involves planting a variety of crops within a farming system, diverging from monoculture. This practice mitigates risks by safeguarding against crop failures from pests or adverse weather (Wang et al., 2021; Kalinga et al., 2022). Diverse crops enhance resilience, as different species tolerate various conditions. Nutrient optimization is achieved through varied nutrient requirements and nitrogen-fixing crops. Pests and diseases are managed naturally, while soil health improves from diverse root structures (Thakur et al., 2023). Market opportunities expand with diverse produce, and cultural traditions are preserved. Adaptation to climate change is also facilitated. Diversification methods include intercropping, crop rotation, and polyculture. This sustainable approach aligns with agroecology, bolstering food systems’ resilience and sustainability (Kerr et al., 2023).
- ii Polyculture: Polyculture involves cultivating diverse crops together or in rotation, fostering biodiversity, nutrient cycling, and pest control. Unlike monoculture, it enhances ecosystem stability, resilience, and resource efficiency. With varied plants sharing resources, soil health improves, while risk from pests and climate variability decreases (Wilson and Lovell, 2016). Polyculture’s cultural diversity and ecological services, like

carbon sequestration, amplify its value. Examples include the “Three Sisters” technique of corn, beans, and squash, and legume-cereal combos. This sustainable practice reflects agroecological principles, promoting resilient and productive food systems while preserving local traditions and enhancing ecosystem health (Al Aysh, 2016).

- iii Integrated pest management (IPM): Integrated pest management (IPM) is a sustainable approach to pest control in agriculture. It combines techniques like monitoring, prevention, cultural adjustments, biological control, and limited chemical use. IPM focuses on minimizing pests’ impact while reducing reliance on synthetic chemicals. Strategies include promoting natural predators, adjusting planting practices, and setting action thresholds. By considering ecosystem dynamics and long-term solutions, IPM maintains crop health, preserves beneficial species, and prevents pesticide resistance. This approach fosters resilient and environmentally friendly agricultural systems, ensuring both productivity and ecological balance (Kabir and Rainis, 2015; Lamichhane et al., 2015).

Improved nutritional outcomes through agroecology

Agroecology prioritizes improved nutritional outcomes by cultivating nutrient-rich crops, promoting biodiversity, and



emphasizing traditional and local foods. Reduced chemical use ensures safer, healthier produce. Soil health enhances crop nutrition, while decentralized systems provide fresher foods (Hunter et al., 2019). Agroecology’s climate resilience sustains nutritional access amid environmental challenges. Empowering small-scale farmers improves food diversity and livelihoods. Knowledge-sharing fosters informed dietary choices. This approach integrates ecology, agriculture, and nutrition, contributing to better overall health and well-being.

Agrobiodiversity and adaptive capacity

Recognizing the significance of agrobiodiversity in adapting to evolving environmental circumstances is crucial for the establishment of robust and sustainable agricultural systems. Diverse crop varieties possess unique traits that enable them to endure stressors, aiding in breeding resilient strains (Kole et al., 2015; Dar et al., 2021). Agrobiodiversity aids climate adaptation by housing genetic material for crops thriving in evolving conditions. Examples highlight agrobiodiversity’s impact, from flood-resilient rice to adaptable tomatoes. Agroecological practices further reduce production risks by emphasizing diversification, integrated pest management, and soil health. Examples, including agroforestry in drought-prone regions and rice-fish farming, showcase successful implementation. These strategies collectively enhance adaptive capacity and promote sustainable food systems (Rao et al., 2016; Rozas et al., 2022).

Significance of agrobiodiversity in adapting to changing environmental conditions

The significance of agrobiodiversity in adapting to changing environmental conditions is paramount for resilient and sustainable agricultural systems. Agrobiodiversity, encompassing diverse plants, animals, and microorganisms within agroecosystems, plays a pivotal role due to its genetic resilience. Varied crop varieties possess unique traits that enable them to endure environmental stressors like drought, pests, and diseases, offering potential for breeding resilient strains (Adeleke and Babalola, 2021). Moreover, agrobiodiversity aids climate adaptation by housing genetic material for developing crops thriving in evolving conditions (Kozicka et al., 2020). Its scope extends to ecosystem services, crop and livestock health, nutritional diversity, local adaptation, and cultural heritage preservation. By reducing reliance on limited varieties, encouraging research and innovation, and fostering community-led conservation, agrobiodiversity becomes central to addressing uncertainties in the future. This ensures food security, ecological balance, and sustainable development (Agnoletti and Santoro, 2022).

Examples illustrate agrobiodiversity’s real-world impact. Traditional rice varieties like India’s “Sahbhagi Dhan” show flood resilience (Dar et al., 2021), aiding inundation-prone areas. Heirloom tomato types like “Brandywine” highlight adaptability to varied climates, while Icelandic sheep exhibit hardiness in harsh conditions (Swett et al., 2023). Community-driven initiatives, such as the “Slow Food Presidia,” safeguard crops like Andean “Tarwi,” preserving

cultural heritage and genetics. These instances underscore agrobiodiversity's rich genetic resources, equipping us to tackle environmental challenges while fostering sustainable food systems.

Agroecological practices reducing production risks

Diversification of crops and livestock, crop rotation, and agroforestry are core strategies employed to minimize risks. Natural pest control mechanisms and integrated pest management reduce reliance on chemical pesticides, mitigating the threat of pest resistance. Emphasis on soil health and local knowledge fortifies system adaptability (Bale et al., 2008; Harvey et al., 2014; Piwowar, 2021). Recent examples highlight the efficacy of agroecological practices. In response to climate change, farmers in drought-prone regions have adopted agroforestry, planting trees to alleviate water stress and buffer crops from extreme weather (Akinagbe and Irohibe, 2014). In Cambodia, integrated rice-fish farming enhances pest control and boosts productivity (Halwart, 1998). In the drought-affected regions of Australia, agroecological practices have been successfully implemented to mitigate water scarcity impacts (Wakchaure et al., 2020). Farmers have adopted a combination of practices such as conservation tillage, cover cropping, and rotational grazing. These approaches enhance soil water retention and minimize water runoff, allowing crops and pastures to better withstand extended dry periods (Carr et al., 2013). The result has been increased resilience to drought conditions and reduced vulnerability to water-related production risks.

Agroecological strategies that promote adaptive capacity

These agroecological strategies have been put into practice worldwide, effectively enhancing the adaptive capacity of agricultural systems. Here are examples of each:

- i Diverse crop rotations: In the United States, the corn-soybean-wheat rotation is a classic agroecological strategy that has been widely adopted. This rotation involves alternating the cultivation of corn, soybeans, and wheat on the same field over consecutive seasons. This practice enhances soil fertility by varying nutrient demands and reducing pest buildup, leading to sustainable and resilient crop yields (Mirsky et al., 2013; Huang et al., 2021).
- ii Agroforestry systems: The "taungya" agroforestry system in Southeast Asia combines tree planting with crop cultivation (Paudel and Shrestha, 2022). In Indonesia, farmers plant fast-growing tree species alongside crops like maize and beans (Siarudin et al., 2021). The trees provide shade, improve soil fertility, and serve as a source of wood products. This strategy enhances local adaptation to climate changes and promotes ecosystem services.
- iii Climate-resilient crop varieties: The development of drought-tolerant maize varieties by the International Maize and Wheat Improvement Center (CIMMYT) has empowered farmers in sub-Saharan Africa to withstand changing climate patterns (Simtowe et al., 2019). These improved maize varieties have shorter growth cycles, enabling farmers to avoid drought periods and harvest more reliable yields.
- iv Water management techniques: In India, the System of Rice Intensification (SRI) promotes water-efficient rice cultivation. SRI uses reduced water inputs and spacing between plants, resulting in increased yields and decreased water requirements. This technique has helped farmers adapt to erratic monsoon patterns and water scarcity (Biswas et al., 2019).
- v Cover cropping and mulching: In Brazil, farmers practicing no-till agriculture have adopted cover cropping and residue mulching to improve soil structure and reduce erosion. These practices enhance water infiltration, reduce soil evaporation, and promote overall soil health, enabling adaptation to fluctuating rainfall patterns (Ofstehage and Nehring, 2021).
- vi Intercropping and polyculture systems: In parts of Africa, the "push-pull" intercropping system has been employed. It involves planting maize and sorghum intercropped with forage grasses and desmodium, a nitrogen-fixing legume. Desmodium repels stem borers from the maize and sorghum while providing nitrogen to the soil. This agroecological strategy enhances pest control and soil fertility (Khan et al., 2014).
- vii Traditional and local knowledge integration: The "zai" technique in Burkina Faso involves small pits filled with organic matter, which increase water retention and enhance soil fertility. This technique, based on local knowledge, enables farmers to adapt to drought conditions and improve crop yields (Danjuma and Mohammed, 2015).
- viii Livestock integration: In Australia, holistic planned grazing involves rotating livestock across pastures in a controlled manner. This practice promotes grassland health, reduces soil erosion, and enhances biodiversity. It adapts to changing climatic conditions by ensuring proper land management and sustainable forage utilization (Drewry and Paton, 2000).

Biodiversity conservation through agroecology

Agroecology plays a pivotal role in preserving native species and upholding biodiversity. This holistic approach resonates with ecological harmony and diversity, offering a unique platform for the harmonious coexistence of agricultural practices and native ecosystems. At its heart, agroecology encompasses an array of practices that collectively contribute to the creation of habitats, enhancement of natural pest control mechanisms, and the conservation of genetic diversity. This comprehensive overview delves into the paramount role that agroecology plays in conserving native species, supported by recent and effective implementations (Amekawa et al., 2010; Nikezic, 2022; Shukla et al., 2022). Table 1 presents a diverse range of agroecological activities across 20 countries, showcasing positive impacts on ecosystems. Examples include Spain's "Dehesa" system, preserving critical habitats, and Thailand's rice-fish farming enhancing aquatic biodiversity and providing additional income for farmers. These initiatives

TABLE 1 Agroecological activities across countries and their positive impacts on ecosystems and the environment.

S. No.	Country	Agroecological activities	Positive impact on ecosystem and/or on environment	References
1	Spain	“Dehesa” agroforestry system: coexistence of cork oak trees and grazing lands	Provides essential sanctuaries for the Iberian lynx and numerous bird species, safeguarding critical habitats and ensuring sustainable livestock management	Plieninger et al. (2021)
2	Europe	“Flower strips” in vineyards	Attracts indispensable pollinators, bolstering grape yields and nurturing native bee populations, contributing to biodiversity and enhancing grape production	Kratschmer et al. (2019)
3	India	Revival of indigenous rice varieties like “Mahsuri”	Preserves genetic diversity, showcases resilience against pests and diseases, protecting ancestral agricultural treasures	Singh et al. (2014)
4	Costa Rica	Agroforestry systems within coffee cultivation	Creates essential wintering sites for avian species, mirrors native forests, and advances biodiversity conservation	Häger (2012)
5	Thailand	Agroecological rice-fish farming with sustainable water management practices	Enhances fish biodiversity, offers pest control solutions, and provides supplementary income streams for farmers, positively impacting aquatic ecosystems.	Lu and Li (2006)
6	Mexico	“Milpa” system: Intermixing corn, beans, and squash	Preserves traditional crops while nurturing native species, exemplifying community-driven engagement and fostering cultural heritage and ecological sustainability	Lenné (2023)
7	Spain	“Banc d’Aliments de la Terra” initiative	Safeguards local crop varieties, ensures thriving native species, and underscores agroecology’s role in conserving genetic resources and preserving rich agricultural heritage	González-Puente (2020)
8	Brazil	Establishment of “agroecological corridors”	Seamlessly reconnects fragmented habitats, facilitates movement of native species, amplifies overall biodiversity, and contributes to the restoration of degraded lands	Painter et al. (2022)
9	France	Organic vineyards fostering mycorrhizal fungi	Promotes healthier vines, conserves subterranean biodiversity, and showcases agroecology’s positive impact on soil microorganisms and vineyard health	Longa et al. (2017)
10	Uganda	Agroecological coffee farms with shade trees	Provides refuge for wildlife, embodies agroforestry’s role in biodiversity conservation, and supports sustainable livelihoods for local communities	Morris et al. (2016)
11	Canada	Agroecological buffer zones along water bodies	Creation of natural habitat corridors safeguards native plant and animal species, improves water quality, and prevents soil erosion	Gene et al. (2019)
12	Japan	Agroecological rice cultivation with traditional practices	Preserves native rice varieties, maintains soil fertility, and fosters beneficial insect populations, contributing to ecosystem health and resilience	Schrager et al. (2023)
13	Kenya	Agroecological practices in traditional “shamba” gardens	Integrated pest management and intercropping maintain local plant diversity, offer habitat for beneficial insects, and improve soil health in small-scale farming systems	Mukhovi et al. (2020)
14	Australia	Agroforestry systems with native tree species	Supports local biodiversity by providing habitats for native birds, insects, and mammals, while enhancing soil fertility and minimizing erosion in agricultural landscapes	Nichols et al. (2021)
15	Nepal	Agroecological terraced farming practices	Prevents soil erosion, maintains local crop diversity, and minimizes habitat disruption, positively impacting native species and maintaining landscape stability	Chapagain and Raizada (2017)
16	South Africa	Agroecological livestock rotation and managed grazing	Enhances grassland health, reduces soil degradation, and supports native grass and plant species while providing sustainable meat production.	Marandure et al. (2017)
17	China	Agroecological mixed cropping systems	Preserves genetic diversity, reduces pest susceptibility, and enhances soil fertility, contributing to the conservation of native plant species and resilient agricultural systems	Niggli et al. (2021)
18	Peru	Agroecological practices in Andean potato cultivation	Integrating traditional farming knowledge and diverse potato varieties conserves genetic diversity, safeguards local food security, and supports native ecosystem dynamics	Zimmerer et al. (2002)
19	Nigeria	Agroecological practices in yam cultivation	Intercropping and reduced chemical use sustain soil health, promote beneficial insects, and foster native plant species alongside yam production	Bamire and Amujoyegbe (2005)
20	Madagascar	Agroecological rice-fish farming in wetlands	Conserves wetland ecosystems, sustains native fish populations, and supports bird species while providing food and livelihoods for local communities	Koohaikan and Furtado (2004)

demonstrate agroecology's potential to contribute to environmental sustainability and biodiversity conservation globally.

Biodiversity-boosting farming techniques

Agroforestry, cover cropping, and reduced chemical inputs are sustainable farming methods that significantly enhance biodiversity (Rosati et al., 2021). Agroforestry involves integrating trees into agricultural areas, providing habitats for wildlife and stabilizing soil (Yadav et al., 2019). Cover cropping, using diverse non-cash crops, protects soil from erosion, enriches it with organic matter, and fosters beneficial insects and pollinators. Minimizing synthetic pesticides and fertilizers reduces harm to non-target organisms, allowing natural pest control and soil health recovery (Kocira et al., 2020). These practices create multifaceted habitats, improve soil structure, and encourage diverse microbial communities. By mirroring natural ecosystems, these approaches establish resilient environments for various species. Together, they promote ecological balance while maintaining agricultural productivity.

Agroecology's role in climate change mitigation

Agroecology fosters a symbiotic link between carbon sequestration and soil health, promoting practices like cover cropping and reduced tillage (Giri and Madla, 2017). By mitigating emissions through crop diversification and eco-friendly approaches, agroecology emerges as a resilient, community-driven solution, contingent on supportive policies and resources.

Carbon sequestration

The process of removing carbon dioxide (CO₂) from the atmosphere and storing it for a long time is known as carbon sequestration. This process, as it relates to agriculture, entails storing carbon in soils, plants, and other natural systems after it has been captured through a variety of methods. Increasing the amount of organic matter in soils by techniques like cover crops, reduced tillage, and adding organic amendment is one of the main ways to sequester carbon (Nogia et al., 2016).

Soil health improvement

Soil health encompasses the physical, chemical, and biological well-being of soils. Healthy soils are more resilient, productive, and better able to support plant growth. Practices that improve soil health include adding organic matter, practicing crop rotation, reducing soil disturbance, and minimizing chemical inputs (El-Ramady et al., 2014). These practices enhance soil structure, water retention, nutrient availability, and beneficial microbial communities.

Carbon sequestration and soil health are closely linked. Increasing organic matter in soils not only stores carbon but also improves soil structure and water-holding capacity. This, in turn, supports plant growth, enhances nutrient cycling, and reduces erosion. Healthy soils with adequate organic matter provide a more favourable environment for beneficial soil organisms, such as earthworms and mycorrhizal

fungi, which aid in nutrient uptake and contribute to overall ecosystem resilience.

Agroecological practices that reduce greenhouse gas emissions

Crop rotation and diversification interrupt disease and pest cycles, diminishing the reliance on synthetic pesticides and fertilizers (Tariq et al., 2019). Moreover, these practices bolster nutrient cycling, enrich soil health, and curtail the release of nitrous oxide, a potent greenhouse gas, from fertilized soils. Cover cropping, adopted during fallow periods, captures atmospheric carbon dioxide and mitigates soil erosion. Integration of agroforestry systems intertwines trees with crops or livestock, storing carbon within woody biomass and soil repositories. Trees also provide shading, ameliorating heat stress in livestock and crops and subsequently reducing emissions from energy-intensive cooling systems (Medhi et al., 2021).

Progressive livestock management, particularly rotational grazing, fosters pasture recovery and curtails methane emissions resulting from enteric fermentation. This strategy also enhances carbon sequestration in grasslands. Integrated pest management (IPM) prioritizes natural predators and beneficial insects for pest control, mitigating reliance on chemical pesticides. This approach maintains ecological equilibrium, limiting ecosystem disruption and potential greenhouse gas emissions linked to pesticide production and application (Alliance Environnement, 2019; Desneux et al., 2022).

Agroecological nutrient management emphasizes organic amendments, elevating soil organic matter content and diminishing synthetic fertilizer necessity. This, in turn, reduces emissions linked to fertilizer production and restrains nitrous oxide release from fertilized soils. Localized food systems decrease emissions linked to long-haul transportation and storage. Consumption of locally sourced produce enables communities to mitigate the carbon footprint of their diets. Traditional indigenous practices, grounded in generations of wisdom, often underscore agroecological techniques that maintain soil health and resource sustainability, resulting in reduced emissions compared to conventional methods (Raza et al., 2022; Enthoven and Van den Broeck, 2021).

Climate-resilient farming systems

Agroecology offers a promising path towards climate-resilient farming systems by integrating ecological principles into agriculture. Diversification of crops and livestock, prioritizing soil health through reduced tillage and organic practices, and promoting biodiversity for pollination and pest control are central to its approach (Leippert et al., 2020). Agroecology also emphasizes the use of traditional and locally adapted crop varieties, which are more resilient to changing climate patterns. By reducing dependency on external inputs and enhancing water management strategies, it helps farmers cope with water scarcity and extreme weather events (Sinclair et al., 2019). Moreover, agroecological practices foster community-based knowledge sharing, enabling flexible adaptation to local conditions. To fully unlock its potential, supportive policies, education, and resources are crucial for enabling farmers to implement these practices effectively.

Case studies and success stories

Diverse agroecological initiatives worldwide, showcasing their transformative impact on agriculture, livelihoods, and sustainability. Highlighting cases from Andhra Pradesh (India), Mexico, Malawi, Cuba, Asia, Africa, and Latin America, it illustrates how community-managed natural farming, research-driven programs, agroforestry, agroecological revolutions, systematic rice intensification, conservation tillage, and farmer-driven knowledge sharing contribute to enhanced food security, biodiversity preservation, and climate change mitigation.

Andhra Pradesh community managed sustainable agriculture

The Rythu Sadhikara Samstha, Government of Andhra Pradesh, is driving a transformation impacting 50 million people, including 6 million farmers and 8 million hectares of land. Named the Andhra Pradesh Community-Managed Natural Farming initiative, it shifts toward systemic agro-ecology, empowering small-scale farmers and maintaining ecological balance. Noteworthy for involving local communities, the initiative advocates agroecological practices like organic farming and integrated pest management. The initiative enhances farmer livelihoods, soil fertility, and biodiversity, demonstrating the integration of agroecological principles for resilience, sustainability, and community empowerment (Bharucha et al., 2020; Prabhu et al., 2022).

MasAgro in Mexico

MasAgro is a research for development program in Mexico that aims to increase the productivity and sustainability of maize and wheat production. It stands for “Mas Alimentos, Mas Ingresos, y Mas Sustentabilidad en el Agro” in Spanish, which translates to “More Food, More Income, and More Sustainability in Agriculture” in English. The program is designed to address the challenges of food security, poverty alleviation, and environmental sustainability (Martínez-Cruz, 2020; González-Abraham et al., 2023).

Agroforestry in Malawi

Intercropping maize with *Faidherbia albida* trees boosts soil fertility, yielding up to 280% more maize. The Changu Changu Moto Stove Project distributes efficient stoves, promoting sustainable woodlot management and curbing deforestation. Smallholders thrive by integrating fruit trees like mangoes, enhancing nutrition, income, and crop shading. These cases highlight agroforestry’s role in bolstering yields, curbing deforestation, and diversifying livelihoods. To harness its benefits, knowledge sharing, supportive policies, and research are vital. Malawi’s embrace of agroforestry promises a resilient and prosperous agricultural future (Ekyaligonza et al., 2022; Dierks et al., 2021).

Cuba’s Agroecological revolution

Cuba’s Agroecological Revolution has evolved over decades, reflecting a continuous journey of change and innovation. In the

1960s–1970s, the country leaned on chemicals and machinery, aided by the Soviet Union, embracing monoculture practices. The 1990s brought the “Special Period” post-Soviet collapse, inducing economic hardships. Without external support, agricultural reliance on imported resources declined, causing food production setbacks. Responding to the crisis, Cuba initiated sustainable alternatives in the 1990s. Organic and agroecological experiments surfaced, focusing on smaller-scale, self-reliant systems. In the late 1990s and 2000s, Cuba officially endorsed agroecology, championing urban farming via the “Programa de Agricultura Urbana.” The nation turned to diversified, community-based approaches, emphasizing local cultivation in home and urban gardens. Throughout the 2010s, agroecology’s influence expanded across urban and rural domains. Organic farming, traditional seed conservation, and natural pest control garnered attention. Vibrant farmers’ markets and local networks bolstered access to fresh produce (Altieri and Toledo, 2011; Machado, 2017).

Systematic Rice Intensification

The System of Rice Intensification (SRI) has achieved remarkable success across Asia. From India to China, Indonesia to Vietnam, and Bangladesh to Cambodia, SRI’s innovative practices have led to significant yield increases and improved sustainability (Upboff, 2008). By optimizing planting techniques, water management, and organic matter incorporation, SRI has become a vital tool in enhancing rice production, boosting food security, and promoting sustainable agricultural practices throughout the region. SRI has been practiced in various provinces of China, with substantial yield increases observed. Some regions have reported yield improvements of 30–50%. Chinese farmers have adapted SRI techniques to suit local conditions and water availability (Ly et al., 2012).

African Conservation Tillage Network

African Conservation Tillage Network: This network promotes conservation tillage practices across Africa, minimizing soil disturbance and maintaining crop residues on the field. These practices improve soil structure, water retention, and nutrient availability, leading to enhanced yields and reduced erosion (Steiner and Bwalya, 2003).

Campesino a campesino movement in Latin America

This movement facilitates knowledge sharing among small-scale farmers. By exchanging traditional farming practices and adapting them to local conditions, farmers across Latin America have improved their yields, diversified their crops, and reduced their reliance on external inputs (Holt-Giménez, 2006).

Challenges and barriers

Agroecological adoption encounters hurdles like knowledge gaps, technological constraints, and risk aversion. Policy challenges

involve regulatory frameworks, limited support, and economic pressures, while cultural barriers include traditional beliefs and societal norms. Overcoming these challenges is vital for sustainable agriculture.

Obstacles in adopting agroecological practices

Agroecological practices represent a promising avenue for achieving sustainable agriculture, yet their widespread integration encounters multifaceted challenges requiring meticulous examination. A significant impediment lies in the gap of knowledge and awareness, as farmers, extension services, and policymakers often possess limited comprehension of agroecological principles, necessitating comprehensive educational initiatives for effective implementation (Leippert et al., 2020). Moreover, technological and infrastructural constraints hinder adoption, with farmers facing barriers in accessing requisite innovations, thereby impeding the transition from conventional methods (Boulestreau et al., 2021). Additionally, risk aversion stemming from uncertainties surrounding agroecology may dissuade farmers from embracing novel practices, mandating the demonstration of benefits and risk mitigation strategies (Chèze et al., 2020). Concerns over short-term yields further exacerbate reluctance, underscoring the importance of conveying the long-term advantages such as enhanced soil health and resilience (Kipling et al., 2019). Policy and market challenges compound the issue, with inadequate support and incentives discouraging agroecological adoption, necessitating policy interventions like subsidies and market promotion (Mockshell et al., 2023). Fragmentation of agroecological knowledge exacerbates adoption hurdles, highlighting the imperative of integrating and disseminating localized knowledge (Takahashi et al., 2020). Labor and time intensity associated with some practices pose additional barriers, particularly in regions grappling with labor shortages. Socioeconomic factors further complicate matters, as poverty, limited access to credit, and gender disparities inhibit adoption, underscoring the necessity for inclusive solutions addressing these challenges (Rao and Moharaj, 2023). Moreover, resistance to change, entrenched by farmers' attachment to conventional practices, necessitates showcasing successful case studies and engaging farmers in experimentation to foster acceptance (Antwi-Agyei and Stringer, 2021). Lastly, efforts to scale up agroecological practices encounter limitations in extension services and technical support, warranting bolstering of these services to facilitate broader adoption (Autio et al., 2021).

Policy, economic, and cultural challenges

Agroecological practices represent a promising avenue for achieving sustainability and resilience in agricultural systems, yet their widespread adoption encounters multifaceted challenges spanning regulatory, economic, and cultural spheres. Regulatory frameworks, often shaped by industrial agricultural paradigms, may pose barriers to the incorporation of diverse and environmentally friendly methods (Morel et al., 2020). Additionally, limited government support, including insufficient funding, extension

services, and incentives, impedes the transition to agroecology, particularly when policies favoring large-scale monocultures and chemical inputs are entrenched (Blair, 2020). Economic hurdles further complicate matters, as short-term profit pressures and inadequate access to resources deter risk-averse farmers from embracing agroecology, perpetuating disparities within the agricultural sector (Boswijk, 2021; Migliorati, 2023). Cultural challenges, including entrenched traditional beliefs and knowledge systems resistant to change, present significant obstacles, necessitating a nuanced approach to reconcile indigenous wisdom with modern agroecological insights (Swiderska et al., 2022). Moreover, social norms and perceptions, influenced by peer pressure and societal expectations favoring conventional practices, impede the widespread adoption of agroecological methods, underscoring the importance of fostering a shift in mindset and fostering social acceptance (Oteros-Rozas et al., 2019).

Future directions and recommendations

Promoting agroecology adoption involves diverse strategies like education, demonstration farms, policy support, research, extension services, market access, networks, incentives, partnerships, advocacy, and awareness. Crucial advancements in research, policy, and education underpin agroecological success.

Strategies to promote wider adoption of agroecology

Promoting the wider adoption of agroecology necessitates a comprehensive and interdisciplinary approach that encompasses agricultural, policy, educational, and community dimensions. Agroecology, grounded in sustainable and holistic farming principles that emulate natural ecosystems, holds promise for both environmental conservation and agricultural productivity. Strategies to foster its broader acceptance include educational initiatives aimed at empowering farmers with agroecological knowledge through workshops and resource dissemination, alongside the establishment of demonstration farms to tangibly exhibit the benefits of agroecology. Advocacy for pro-agroecology policies, such as incentivizing sustainable practices and integrating them into national agricultural frameworks, is imperative. Furthermore, investments in research and technological innovation are crucial for validating and optimizing agroecological methods. Strengthening extension services to provide tailored guidance on agroecology, developing local markets and supply chains for agroecological products, and fostering collaborative networks among farmers are essential components of the approach. Financial incentives, including grants and tax breaks, can serve as catalysts for farmers to embrace sustainable practices, while partnerships with various stakeholders amplify resources and outreach efforts. Advocating for policy changes grounded in evidence and promoting public awareness of agroecology's multifaceted benefits are vital for driving its widespread adoption. Additionally, providing support and assistance to farmers transitioning to agroecological practices is essential for overcoming challenges and ensuring a smooth

transition. Overall, a concerted effort across multiple fronts is indispensable in realizing the transformative potential of agroecology in modern agriculture.

Research, policy, and education to advance agroecological principles

Advancing agroecological principles necessitates a coordinated and multidisciplinary approach encompassing research, policy development, and education. These three key areas play a pivotal role in driving the adoption and integration of sustainable farming practices that align with agroecology's principles.

- i Research: In research, prioritize comprehensive, long-term studies comparing agroecological practices to conventional methods. Beyond yields, assess ecological, economic, and social impacts. Rigorous research offers empirical evidence, highlighting agroecology's advantages and challenges. Investigate its contributions to vital ecosystem services like pollination, soil health, and water conservation for broader adoption. Understand agroecological principles' role in climate resilience, exploring diversified cropping and agroforestry's impact on shifting climate patterns. Collaborate with indigenous communities, merging traditional knowledge with modern science to enhance sustainability. Explore innovative technologies aligned with agroecology, such as precision farming for low-input systems, providing practical solutions.
- ii Policy: In policy, fostering agroecology requires subsidies and incentives for transitioning from chemical-intensive methods. Clear standards and certifications boost credibility and adoption. Land tenure security prevents displacement. Adequate research funding empowers innovative, sustainable solutions. Mandating government food procurement from agroecological farms supports local farmers and sustainability.
- iii Education: In education, integrating agroecological principles into curricula nurtures informed agricultural professionals who understand sustainability. Training extension workers and farmer field schools offer practical support. Model farms exemplify agroecology's success, while digital platforms share resources, benefiting those with limited formal education. This approach equips individuals with skills for implementing sustainable practices, driving agroecological adoption.

Conclusion

The review covers agroecology's numerous contributions to biodiversity protection, climate change mitigation, sustainable food systems, and adaptive ability. Agroecological approaches, which emphasize crop diversification, polyculture, and integrated pest management, improve yield stability and resilience in food production. Furthermore, agroecology improves nutritional results while addressing global food security challenges. Agrobiodiversity emerges as a significant tool for reducing production risks and increasing adaptive ability in the context of changing environmental conditions. The

interdependent link between agroecology and biodiversity conservation is investigated, illustrating how agroecological practices protect local species while increasing biodiversity in agricultural environments. Notably, agroecology aids in climate change mitigation by sequestering carbon, enhancing soil health, and lowering greenhouse gas emissions, so encouraging the development of climate-resilient farming systems. Case studies from varied locations like Andhra Pradesh, Mexico, Malawi, and Cuba demonstrate both the effectiveness and scalability of agroecological techniques in a variety of agricultural situations. Nonetheless, the analysis recognizes challenges to wider adoption, such as farm-level limits and broader legal, economic, and cultural problems. Overcoming these limitations is critical to realizing agroecology's full potential in promoting sustainable agriculture. Looking ahead, the article proposes measures for integrating agroecology, such as encouraging research, adopting supporting policies, and expanding educational programmes to spread agroecological ideas. Finally, the review closes with a positive prognosis on agroecology's revolutionary potential to advance sustainable and resilient agricultural systems.

Author contributions

Vikas: Conceptualization, Formal analysis, Writing – original draft. RR: Supervision, Writing – review & editing.

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Conflict of interest

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

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