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Organic Approaches for Preserving Soil Health in the Mountainous Agro-Ecosystem of Nepal: A Review

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ABSTRACT

Organic systems emerged as a remedial practice to the overuse of synthetic agrochemicals in the aftermath of the Green Revolution. The devastating consequences of agrochemicals on soil health, microbial ecology and the environment triggered the need for conservative methods of agriculture in the long term. This review aims to explore the challenges, feasible approaches and benefits of preserving soil health over the mountainous agro-ecosystem of Nepal. It suggests the benefits of applying organic approaches like composting, green manuring, biofertilizers, reduced tillage, cover cropping, mulching and agroforestry to preserve soil health for agriculture over the mountains. The fragile terrain and annual monsoon precipitation cause soil degradation, affecting soil properties, microbiomes, vegetation, forest components and biodiversity over the region. These methods are proven to be supportive of erosion control, water retention, emissions reduction, biodiversity conservation, lowering chemical dependency and sustainable farming. Hence, this review, based on extensive studies, provides valuable information on preserving the soil health and agricultural ecosystem in the mountainous part of Nepal, thus bolstering the farming conditions contributing to the livelihoods of farmers and agrobiodiversity preservation.

KEYWORDS

Agro-ecosystem, biodiversity, erosion, organic, conservation, sustainable farming, chemical dependency

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INTRODUCTION

An ecosystem is a complex system of living organisms, their physical environment and all their inter-relationships in a particular unit of space. Likewise, the agro-ecosystem is part of the ecosystem, that is dominated by agriculture and includes assets like biodiversity, ecological succession and food webs, affecting the region impacted by agricultural activity, such as species complexity and energy flows. The mountainous agro-ecosystem in Nepal includes diverse crop cultivation, changing lifestyles, declining soil fertility and deteriorating farm-forest relationships[1]. High mountainous farming, especially for traditionally overlooked crops, has a good foundation for organic agricultural growth due to its traditional integrated farming system and isolated location.

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Soil health refers to a soil's ability to operate effectively within an ecosystem, sustain biological productivity, preserve the quality of the environment and promote the well-being of animals and plants[2]. It encompasses physical, chemical, biological and hydrological characteristics, with parent rock materials and weathering influencing nutrient availability, impacting plant growth and ecosystem productivity. Soil in Nepal's mid-hills is influenced by various land use systems, the conventional farmlands have lower soil health than pasture and forest regions, indicating a need for development[3]. The soil quality degradation is a scorching issue, especially caused by harsh terrain, steep topography, fragile geological conditions and soil run-offs, all contributing to the mountainous production deficit, putting the region's food security at risk. It necessitates studies and actions on soil conservation over the region that can be assured through the implementation of organic systems.

Organic methods improve soil chemical properties, increase nutrient availability, raise organic carbon content and ultimately contribute to sustainable crop yields[4]. Thus, organic farming is a production system that sustains the soil health, ecosystems, food security and livelihood of people over the mountainous ecosystem of Nepal. The strategies, such as cover cropping, crop rotations, mulching and reduced tillage improve soil structure, nutrient cycling and microbial communities, all of which are necessary for sustainable agriculture and soil health management[5].

So, this study focuses on biological methods of soil conservation addressing the issues of erosions, runoffs and soil degradation over the mountainous region of Nepal making agriculture more challenging. It examines organic methods like cover cropping, crop rotations and reduced tillage, which can enhance soil structure, nutrient cycling, microbial diversity and reduce emissions. This extensive study contributes to academic knowledge on the benefits of organic systems for soil conservation and resilience against climate challenges, ultimately supporting rural livelihoods in Nepal. It explores the agro-ecosystem, organic approaches and challenges in the mountains, emphasizing organic procedures as revolutionary ways to save soil heritage from various constraints and improve productivity for sustainable agriculture.

Overview of the agro-ecosystem in Nepal: Nepal is a landlocked nation in Southern Asia between China and India with a more than 29 million population and an area of 147,516 km^2. It is home to eight of the world's ten highest mountains, including Mount Everest and has fertile plains, sub-alpine forested slopes, temperate highlands and tropical lowlands with variability of climates, resources, vegetation and inhabitants. Nepal has three topographical divisions: The Mountains, Hilly and Terai, spanning from 60-8848 m in Altitude. Almost 77% of the total area of Nepal is composed of rugged hills and rocky-snowy mountains. This section illustrates the overall ecosystem of Nepal along with the climatic variations, soil types, biodiversity, farming practices and organic practices.

Climates: Nepal's five seasons are winter, spring, summer, monsoon and autumn, ranging from the tropical Terai to the high Himalayas. The climate of Nepal is affected by two major weather systems, the summer monsoon (June-September) and westerly circulation (November-May). More than 80% of the annual rainfall occurs over the region of the Himalayas within the monsoon months of June to September[6]. So, the summer monsoon determines the productivity of summer crops in the sloppy mountains, foothills and plains of Nepal contributing to farmers' annual cropping activity as well as the country's economy[7]. Extreme monsoon rains and glacial lake outburst floods have increased soil erosion, floods and landslides in the region[8]. Soil quality has degraded, agricultural lands and crops are often destroyed and emissions have been escalating climate change in the present context of Nepal. According to Pradhan *et al.*[9] agriculture, forests and land use practices contribute to more than 80% of Greenhouse Gas (GHG) emissions throughout the country. Though the mountainous soils act as a carbon sink that contributes to the reduction of atmospheric CO_2 concentration attenuating the greenhouse effect[10], unsustainable farming practices have impacted the soil organic carbon (SOC) loss leading to GHG emissions[11].

Table 1: Figure of available agrobiodiversity in the country

Organisms	Agricultural species	Total species
Microorganisms (fungi, lichens, algae and bacteria, etc.)	800	3,754
Insects (moths, butterflies and worms, etc.)	3,500	10,004
Aquatic species (fish, molluscs and crustaceans, etc.)	250	544
Mammals, amphibians, birds and reptiles	35	1,315
Lower plant species (bryophytes, pteridophytes and gymnosperms)	30	1,710
Higher plant species (angiosperms)	2,003	6,973
Total	6,618	24,300

Source: Joshi *et al.*[14]

Biodiversity: The integrated ecosystem of Nepal comprises farmland, forest, grassland and water resources and biodiversity. The latest figures suggest, there are 118 ecosystems and 75 vegetations across the country[12]. The forests play a crucial role in biodiversity conservation in Nepal, with maintenance of at least 40% of forest cover as mandated by the constitution to ensure environmental equilibrium[13]. According to the forest research and training centre, Nepal (FRTC, 2022), about 41.69% of the entire area of the nation is covered by forest, farmland covers 24.21%, grassland 13.27% and water bodies 0.48% of the total surface area of the country. With its land covering 0.1% of the total global landmass, Nepal shelters 3.2% of the flora and 1.1% of the fauna present in the globe with 5.2% of mammals, 9.5% of birds, 5.1% of gymnosperms and 8.2% of bryophytes discovered worldwide[12]. Despite the small landmass of the country, 24,300 biological species are documented in Nepal, with a species richness of 3,785 species of agricultural fauna and 2,833 species of agricultural flora[14].

Agrobiodiversity, a crucial subset of biodiversity, is divided into six components in Nepal: The crops, forages, livestock, aquatic, insects and microorganisms. From Table 1, Nepal inhabits a total 24,300 of living species, out of which only 6,618 species fall under agrobiodiversity. The species richness of insects (3,500) is higher in the pool of agrobiodiversity followed by angiosperms (2,003) and microorganisms (800), while the lower plant species have the lowest richness (30). Likewise, the soil ecosystem comprises microbial organisms with an abundance of 3,754 microbial species, of which 800 are beneficial making a vast micro-ecosystem below the soil[14]. So, the soil is a significant part of the ecosystem connecting the chain of multiple ecosystems and it's considered to be formed by geochemical processes and climatic interactions.

Soils: According to the Soil and Terrain (SOTER) classification, there are five major types of soil in Nepal. Alluvial soil, sandy and alluvial soil (also called lacustrine soil), gravely soil, residual soil and glacial soil[15]. Soil condition in Nepal varies from different topographies, mountains and plains with variations in soil components and properties. They show varying pH levels (5.3-9.1) and organic carbon content ranging from 0.20-8.56% with forests in Bajhang and farmlands in Mustang consisting highest carbon content[16]. Land use changes in the mountainous terrains, particularly an increase in agricultural lands, have intensified water erosion issues, with agricultural areas facing the most severe degradation compared to forests[17]. Additionally, the outmigration of people from the mountains is leading to land abandonment, causing negative impacts of encroachment by invasive species and soil fertility decline, despite some areas showing increased vegetation cover due to favorable conditions[18]. Also, land abandonment in mountains has reduced soil erosion rates by 51.5% from 1995-2020, demonstrating a positive impact on soil health in the region[19]. The mountainous soil exhibits varying soil erosion rates, with the middle mountains having the highest erosion rate of 38.0 t/ha annually, with significant conservation challenges[20]. Hence, the mountainous soils are fragile, facing degradation due to the issues of erosion, acidity, flooding, nutrient depletion and compaction[21].

Farming practices: As of Statista 2024, agriculture covers 21.06% of the total GDP of the country as the top economic activity in the year 2022. It was 25.16, 24.90 and 23.45% in the years 2019/20, 2020/21 and 2021/22, respectively as reported by Nepal Rastra Bank (NRB, 2021/22). The declining AGDP of the country

is primarily caused by the out-migration of people and a lack of technological advancement[22]. The economy of the country is substantially attached to the agricultural components as 67% of the total population with 62% of total households directly engaged in farming practices, in over 2.21 million hectares of land according to the National Sample Census of Agriculture, Nepal 2021/22. Usually, the people in the mountains of Nepal are involved in economic activities such as subsistent farming, ecotourism and foreign employment, which are vital for their livelihoods and local economy[23].

Terrace farming is a popular system in the sloppy land structure of hills and mountains of Nepal that involves cultivating on flat terraces and utilizing vertical walls[24]. People practice subsistence farming in the hills integrating livestock, crops and agroforestry practices. They grow vegetables like potatoes, beans, grains like maize, millet, buckwheat, barley and rice in mainly rainfed with some micro-irrigation systems[25,26]. The practices of rainwater harvesting and applications of Farmyard Manure (FYM) are widespread among organic as well as inorganic farmers. As agrochemicals are overused to meet the needs of a growing population, indigenous knowledge of agricultural practices is being limited which is making the agricultural system unsustainable[27]. In this regard, the idea of organic agriculture offers itself as a workable and practical substitute, changing the agricultural system's emphasis from productivity to sustainability and creating an agroecologically friendly production system.

Organic practices: Organic agriculture in Nepal is still in its preliminary stages with slow growth and is mainly focused only on export-oriented commodities such as apiculture, coffee, tea, large cardamom, ginger and lentils, etc.[28]. It was officially been promoted in the 10th Five-Year Plan of Nepal and commercial organic farming started after the 1990s[27]. The Government of Karnali Province has ambitiously set a policy to transform the whole province into a fully organic province guided by the "Karnali Province Organic Agriculture Act-2076". Before that, Jumla was declared as the first organic district of Nepal in 2007 and the use of agrochemicals was banned[29]. Remarkably, the officially certified land for organic farming is around 11, 951 ha in Nepal which is only around 0.3% of the total cultivated land area of the country as per IFOAM, 2020. Also, farmers in low-productive and remote regions are shifting back to organic farming for crop production due to the unavailability of chemical fertilizers, mechanizations and inputs[30].

Several organizations are working in the sector, including The Institute for Sustainable Agriculture, Nepal (INSAN), which first began the organized movement of permaculture in 1986 as an alternative to agrochemicals[31]. Then after, some scattered support systems by several NGOs and several private organizations have been working for extension and services along with the provision of subsidies to some growers[27]. Currently, private certifying bodies such as organic certification Nepal (OCN) are executing this standard in the certification process of the farms that follow a set of procedures. Organic certification ensures organic producers adhere to quality standards and environmentally sound production processes, providing third-party confirmation and market confidence through plant and animal health, pest management and judicious material use[32].

Challenges in conserving soil over the mountains: Mountain people in Nepal usually engage in farming and face various physical, climatic, biological, socioeconomic and institutional hurdles, so the major challenges for soil health preservation over the mountains of the country can be classified as below.

Physical challenges: The challenges in conserving soil health in Nepal's mountains include steep slopes, unstable geology and intense monsoon rains that accelerate soil erosion via run-offs causing fertility loss and impacting agriculture[33]. Additionally, landslides and watershed degradation due to geological fragility have an impact on sustainable land resource management[34]. Like erosion by water, wind erosion is also a significant factor contributing to soil fertility decline in Nepal requiring proper vegetation cover and tillage practices to alleviate soil loss[35]. Around 4% of the total land area of the country faces soil loss due

to wind erosion[36]. Acidic soils, low nutrient levels and increased biomass removal are the main obstacles in protecting the soil components in steep terrain from a nutrient perspective. So, the farmers must adjust cropping intensity because of the high land-use pressure for productivity resulting from small and fragmented lands and encourage them to plant N-fixing plants[37]. Contemporary land use practices, land abandonment, deforestation and urbanization all impact ecosystem services negatively requiring effective landscape planning and policies[38]. Heavy metal accumulation in soil from nearby residences and industries rapidly deteriorates soil health and requires bioremediation techniques like plant growth-promoting rhizobacteria for soil revitalization[39]. In a similar vein, forest fires and burnings can deplete SOC, impacting soil health and enhancing GHG emissions[11], all these alerting problems of nutrient depletion and heavy erosion require immediate attention and management techniques.

Climatic challenges: Extreme weather events in the mountains in Nepal, like heavy rainfall and drought, exacerbate challenges by triggering soil erosion, leading to SOC loss and reduced soil health[11]. The issues of varying climates, temperature shifts, heavy precipitation and extreme events, are not only impacting the soil creating erosions but also triggering the issue of agriculture and food security, necessitating adaptation strategies for conservation efforts[40]. Abiotic stresses impact microbial communities declining their colonies ultimately affecting the soil health and properties[41], which is crucial for plant growth and ecosystem functioning by yoking plant-microbe interactions[42]. Climatic extremities of heavy rain causing runoffs, leaching, erosion and landslides are the major challenges over the mountains to preserve the soil properties.

Biological challenges: Overgrazing, deforestation, use of synthetics, land use practices, etc. are some biological constraints on soil conservation. Overgrazing in mountainous grasslands also accelerates soil erosion leading to land degradation and loss of soil properties[43], as the estimated total soil loss rate throughout the country is 25 ton/ha/year with a total annual loss of 369 ton[36]. Deforestation is yet another scorching problem in Nepal that depletes SOC, leading to soil degradation, reduced productivity and increased GHG emissions[11]. The practices of afforestation in the mid-hills have proven to improve soil health by enhancing infiltration rates, reducing compaction and minimizing surface runoff[44]. Deforestation not only impacts soil health but also perishes the abundance of biodiversity present in the ecosystem disrupting their habitats and reducing genetic diversity[45]. The biodiversity loss triggers and boosts the rapid degradation of soil properties by reducing natural processes of nutrient cycling making them vulnerable to pollution[38]. In a similar vein, the abundance of invasive species of plants in the ecosystem is also hazardous for the soil, they cause habitat degradation and native species displacement, thus instigating negative effects on farming communities[46]. Likewise, unsustainable farming practices and excessive application of N fertilizers and organics affect soil and environmental quality through soil acidification, nitrogen leaching in the groundwater and nitrous oxide (N_2O) emissions[11]. There have been challenges in mitigating GHG emissions due to the loss of the tendency of soil to capture atmospheric carbon, which as a result impacts the overall climatic scenario of the country.

Socio-economic challenges: The socio-economic challenges in conserving soil health in Nepal's mountains include small landholdings, male outmigration, poverty and food insecurity, hindering agricultural growth and sustainability though they have opportunities in agroforestry, niche value chains and ecosystem services for livelihood improvement[1]. Likewise, traditional practices, land size, literacy, cash crop farming, off-farm work, caste, group membership and credit use are the barriers to adopting the soil conservation methods over the middle mountains[47]. Other challenges include labour scarcity, limited road access for heavy machinery and poor technological access to farming[48]. Nepalese farmers are gaining familiarity with organic farming but people in remotes are unaware of such sustainable practices, though over 50% of farmers claimed to have heard of and understood organic farming[49]. Similarly, the bio-economic analysis in Nepal's mid-hill region reveals that soil conservation technologies face short-term economic challenges to promote adoption emphasizing the need for capital and initial financial support[33].

Policy and institutional challenges: Soil issues in Nepal are believed to be guided by weak policy regulations, low prioritization and natural forces, posing political challenges[21]. The organic systems require organic fertilizers and equipment, the Nepal government has provided subsidies for chemical fertilizers making them more accessible to purchase at lower cost, but not many efficient policies for organic sources[30]. The government of Nepal started subsidizing biofertilizer production in Nepal in 2011, especially for vermicompost, with a $100,000 budget. However, the program is not effective due to poor nutrient content, lot-to-lot variation, bulkiness and transportation difficulties contributing to its low consumption[50]. Additionally, organic farming in Nepal faces multiple challenges due to the complicated certification process, high costs and strict standards. Limited institutional frameworks and lack of adequate training for extension personnel, limited market access, high supervision costs and discrimination between organic and inorganic products are the other institutional challenges[51]. So, it demands a strong policy for sustainable transitions on the agenda to preserve existing resources.

Organic approaches for soil health preservation: Organic practices increase the biomass of beneficial soil microbes and their diversity which play a key role in determining the soil's structural properties and health[2]. This employs biofertilizer and pest control from animal or plant waste that can be applied as organics for crop improvement and soil health. So, here are some key approaches for maintaining good soil health, focusing on the issues of soil erosion, nutrient leaching and runoffs in mountainous parts of Nepal.

Composting and organic manuring: Since organic agriculture laid the foundation for renewable resources, organic crops are cultivated sustainably utilizing earthworm castings, compost and crop waste utilization in the farming soils[28]. The SOC maintains the quality of soil helping to improve water-holding capacity, stabilising aggregates, reducing erosion and providing slow-release of nutrients[52]. The FYM, compost and green manure are the major sources of organic matter that improve the physical, chemical and biological properties of soil and contribute to the minimization of GHG emissions[53]. Compost and animal manures are the best examples of organic matter as they enhance the physiochemical properties, reduce bulk density, enhance water-holding capacity and promote microbial activities consequently sustaining crop productivity[54,55]. Likewise, vermicompost is a nutrient-rich organic fertilizer and soil conditioner produced by earthworms converting organic waste into valuable worm castings, essential for enhancing soil quality in agricultural practices[56]. It enhances soil health by improving structure, providing essential nutrients, regulating pH and increasing SOC. Additionally, biochar, a charcoal-like carbonaceous solid made by burning organic material is used to incorporate organic matter in soil. It enhances soil health by increasing porosity, expanding water retention, nutrient uptake and creating favourable environments for soil microbiota, combating abiotic stressors and reducing erosion[57].

Green manuring: Green manuring is the process of raising green crops for incorporating them into the soil at the vegetative green stage or flowering stages to improve soil properties[58]. They can be cultivated or wild-grown, with some crops developing nodules for atmospheric nitrogen fixation. Some of the major N-fixing plants for green manuring in Nepal are Sunn-hemp (*Crotalaria juncea*), Dhaincha (*Sesbania* L.), Berseem (*Trifolium alexandrinum*), cowpea (*Vigna unguiculata*), mung bean (*Vigna radiata*) and *Azolla* sp.[58]. These leguminous crops fix atmospheric nitrogen, increasing soil fertility and productivity, as well as plant roots, stubble and straw from pulse crops improve soil properties and nutrient availability[59]. In a similar vein, the use of the N-fixing leguminous tree *Albizia* in higher altitudes, slopes and mountains as hedgerows is effective in regulating the N/P ratios within the soil and making the fertile and productive[60]. The erosion and crop harvesting mismanagements are the main factors responsible for nutrient loss in the middle mountains of Nepal and this depletion of nutrients can be overcome by incorporating green manures in soil or by adding nitrogen-fixing crops in rotation[36].

Cover cropping: The cover cropping is a suggested strategy in mountainous parts of Nepal that preserves soil health by reducing soil erosion, enhancing soil and improving water retention, thus aiding in sustainable agriculture practices[35]. Cover crops are plants that are planted to cover the soil surface to slow erosion, enhance soil-water retention, control pests and diseases and increase biodiversity, thus supporting the agro-ecosystem. Although cover crops are not as widespread in Nepal's cropping system, significant winter vegetables, fodders and leguminous pulse crops such as lentils, chickpeas, field peas, garden peas and kidney beans are planted in the winter[61]. In the hills, most crops are often grown in the summer; in the autumn, sorghum, millet, cowpea and other vegetable crops are grown; in the winter, the land is left fallow until maize is planted. Likewise, annual legumes like *Vicia faba* and *Vida villosa* are suitable for cover cropping in the mid-hills of Nepal, aiding in sustainable farming systems by enhancing soil health and productivity[62].

Mulching: The use of agricultural waste as a mulching material not only increases the physical properties of soil but also enhances soil nutrients[63]. Mulching improves soil properties by soil health and plant growth by retaining moisture, stabilizing soil temperature, enhancing soil structure, suppressing weeds, reducing reflectivity and erosion and lowering maintenance needs[64]. Farmers use mulches mainly for ginger, colocasia, sweet potatoes, vegetables and fruits. It has been demonstrated that applying straw mulch to the soil's surface enhances its chemical, biological and physical characteristics[65]. According to Timsina *et al*.[66] black polythene and silver black mulches aid in weed suppression, soil improvement and increased winter maize productivity in Chitwan, Nepal, showcasing soil health preservation benefits. Likewise, organic mulch improves soil health by increasing soil fertility and moisture retention, optimizing soil temperature, thus reducing surface evaporation and nutrient loss[67].

Reduced tillage: The tillage is the soil preparation for cultivating crops through ploughing. Change in tillage operation results in a change in soil pore characteristics and SOM, which is determined by compaction and fragmentation in the tillage zone[68]. By examining the condition of unsustainable conventional tillage and its effects on soil health, people in high hills of Nepal have chosen reduced tillage as an appropriate method of soil manipulation[31]. It is a part of the conservation approaches to preserving soil health by reducing erosion, enhancing soil structure and promoting microbial activity, subsequently making it beneficial for mountainous regions' sustainability[69]. Reduced tillage in central mountainous regions of Nepal addressed soil erosion challenges that enhanced soil health and nutrient conservation without compromising maize yield[70]. Similarly, Tiwari *et al*.[47] in their studies found that the reduced tillage with some residue retention in the maize-cowpea cropping was more effective in soil fertility conservation, thus increasing farm income compared to the conventional maize-millet system.

Crop rotation and diversification: The crop rotation is the growing of the number of crops in series in a similar cropland. It is effective for nutrient recycling that accelerates soil microbial activity and root physiology enhancing nutrient availability for higher crop yield. Rice-wheat, rice-legume, rice-wheat-maize, rice-rapeseed-maize, rice-rapeseed-rice, maize-soybean-rapeseed-fallow, potato-barley and maize-wheat are some of the most common cropping rotation practices over the mountainous part in Nepal[71]. Crop rotation with legumes is one of the best alternatives for plant nutrient management in many ways such as intercropping, mixed cropping, etc.[59]. Rawal *et al*.[72] in their study to assess the impact of legume rotation and nutrient management on maize performance, found that balanced use of chemical and organic fertilizers in the rotational cropping of grain legumes like chickpeas, lentils and field peas can enhance maize productivity and reduce the need for inorganic nitrogen fertilizer. In contrast to monocultures or crop rotations, crop diversification refers to a set or multiple rotations of three or more crops[73]. As a method of conservation agriculture, crop diversification enhances soil health by reducing soil disturbances, improving biodiversity and promoting sustainable agriculture practices[48]. Also, Ghimire and Bista[74] in their study on the mountainous Nuwakot District in Nepal, found that crop diversification improves soil pH in acidic soils enhancing soil health and overall agricultural sustainability.

Agroforestry: The agroforestry system is an integrated system of growing crops, trees and livestock together to improve soil fertility, conserve soil and water and satisfy food and fuelwood requirements. As a type of agroforestry system, hedgerow intercropping lowers soil erosion rates, increases organic matter and maintains crop yields over time[33]. This system is also known as Sloping Agricultural Land Technology (SALT) or contour hedgerow intercropping system. Hedgerow is growing mainly leguminous crops or N-fixing plants, i.e., with Napier (*Pennisetum purpureum*), Sunn-hemp (*Crotalaria juncea*) and pigeon pea (*Cajanus cajan*) on the terrace edges and risers are proven practices for soil conservation and supplying forages for livestock[75]. Similarly, soil bioengineering methods also successfully stabilize slopes and stop erosion and community involvement is essential to the effectiveness of these vegetation-based methods[76].

Biofertilizers: The biofertilizer is a mixture of microorganisms, primarily bacteria, fungus or cyanobacteria, that when applied to plants or soil, improves plant growth, development and soil quality[77]. They have beneficial microbes that can enhance soil health by improving nutrient availability, structure and resilience to stress, promoting sustainable agriculture practices[78]. The common sources of biofertilizers are *Rhizobium* spp. and *Azolla*, along with blue-green algae (*Anabaena azollae*). Free-living N-fixing bacteria like *Azotobacter*, *Azospirillum* and *Clostridium* spp., can fix nitrogen in non-legume crops like rice, wheat, barley, millet and cotton. Private suppliers in Nepal are supplying liquid formulations of microorganisms, such as effective micro-organisms (EM), Jeevatu and Jibamrit, to farmers on a limited scale, but there is no effective quality control mechanism, which comes from India and is formulated in Nepal[59]. So, in preserving the soil conditions of mountainous terrains, biofertilizers could be significant in aggregating the soil components, continuing the preceding nutrient cycle and accumulating organic matter.

Integrated plant nutrient management (IPNM): The integrated plant nutrient management (IPNM) involves field-level management practices in agriculture for optimizing crop yields and sustaining soil health implementing the application of organic manures, crop residues, chemical fertilizers and bio-fertilizers. Balanced fertilization is an important aspect of IPNM, it could be achieved through the application of multi-nutrients in balanced proportion from fertilizers, organic sources, biological sources and more accurately and precisely through IPNM on a cropping system basis[79]. The IPNM practices in Nepal, especially in hills and mountains, include the integrated use of FYM/compost, inorganic fertilizers, agricultural lime, crop residues/farm waste recycling, catch crops in rotations and agroforestry techniques to improve SOM, preserve soil biodiversity and raise crop yields and income[59]. The study of Chapagain and Gurung[75] also found that integrated plant nutrient management practices can enhance maize yields and soil conservation, with a three-year study showing a 64% increase in grain yield and subsequent millet yield compared to a maize-millet cropping system over the districts of mid-hills in Nepal.

Benefits and prospects

Enhanced soil structure and fertility: Modern practices like intensive tillage, chemical inputs and monoculture contribute to soil degradation, nutrient depletion and environmental pollution, so well-known techniques like cover crops, crop rotation and reduced tillage are recommended for their ability to improve soil[5]. Conventional farming, driven by higher production, fails to replenish the soil's organic content in a ratio comparable to that was lost leading to a gradual decline of soil fertility[11], as soil nutrients are bolstered by adding chemicals fertilizers[80]. In organic systems, nutrients are obtained from degraded materials through the active participation of soil microorganisms, which ensures soil health and soil structure stability, soil aggregate formation and plant pathology[80]. Various organic approaches such as conservation practices, green manuring, composting, mulching, cover cropping, agroforestry, biofertilizers, crop diversification, etc. help preserve soil fertility, composition and crop productivity, which in turn reduces erosion and increases soil stability.

Erosion control: The major challenges in Nepal's slopes of mountains and hilly regions are runoffs and soil erosion, which can be solved by using different organic ways like agroforestry, cover crops, reduced tillage and green manuring. Soil productivity decreases due to soil fertility depletion from continuous

cropping without the incorporation of adequate mineral fertilizers and FYM, as well as soil erosion, leaching and nutrient mining[81]. Reduced tillage is a key conservation practice in organic farming that helps preserve soil health by minimizing erosion, improving soil structure and promoting microbial activity, which is especially beneficial for the sustainability of soil in mountainous regions[69]. Likewise, cover crops offer numerous advantages to the soil ecosystem by preventing erosion, enhancing soil health and increasing water retention capabilities[35]. Similarly, nutrient depletion caused by erosion and poor crop management can be addressed by integrating green manures or nitrogen-fixing crops into crop rotations[36]. Hedgerow intercropping also mitigates soil erosion and improves organic matter content in the soil[33], particularly hedges made of N-fixing leguminous plants are useful for controlling the N/P ratios in the soil and enhancing fertility and productivity for the long term[60].

Soil-water conservation: Cover cropping is highly recommended in Nepal's mountainous region as a strategy to conserve soil moisture, thus improving soil structure and enhancing water retention capabilities[35]. Likewise, organic mulch improves soil health by increasing moisture retention and optimizing soil temperature to reduce surface evaporation and nutrient loss for sustainable soil management[67]. Prasad *et al*.[53] in their study of rice-wheat cultivation systems in Nepal found that the conservation practice of zero-tillage reduces the cost of production, thus reducing water requirements and increasing the crop yield by 16-50% as compared to conventional tillage practices. The FYM, compost and green manures are the organic matters supporting the moisture retention capacity of soil as conservation practices. The organic matter in soil helps to improve water-holding capacity, stabilizes soil components and reduces erosion, hence enhancing crop productivity[52]. Together, these practices play a crucial role in conserving soil water and ensuring the long-term viability of farming in mountainous areas.

Biodiversity conservation: Organic amendments have a significant role in conserving biodiversity as there is a higher degree of presence of biodiversity in organic farms in comparison to conventional farms[82]. The majority of the biodiversity is present in the marginal rainfed lands of developing nations, which can be conserved by adopting organic practices that enhance the higher yield of crops and maintain the productivity of soil, thus reducing biodiversity loss. Organic approaches in farming claim to provide benefits in terms of environmental protection thus increasing the quality of soil, water, air and biodiversity[83]. Mountainous farming systems in Nepal do not consider agrochemicals or else traditional crop varieties predominate in the cultivation practices with a small proportion of cereal production. This substantially bolsters the preservation of native agro-biodiversity over the mountains. Conservation practices, organic manuring, intercropping and agroforestry are some major organic approaches for protecting biodiversity.

Emissions minimization: The impact of organic fertilizers on GHG emissions is a contentious issue, with some studies suggesting they increase emissions of climate-altering gases like CO_2, N_2O, CH_4 and NH_3, while others suggest they store more carbon in soil[84]. According to Dahal *et al*.[82] organic systems have the potential to reduce GHG emissions and strengthen the ecosystems to adapt to climatic impacts, as organic approaches act as carbon sinks and provide a buffer to adapt to environmental stresses. Organic practices reduce the requirements of energy and mineral fertilizers lowering the emission of nitrous oxide (N_2O), minimizing the global agricultural GHG emission by 20%[85]. Studies have shown the positive effects of cover crops, intercropping and farm manure on increased carbon sequestration in the soil carbon pool. In a similar vein, biochar, with its low emission and high sequestration, can significantly contribute to climate change mitigation and GHG compensation. So, emphasizing organic farming can increase SOM and reduce GHG emissions through the process of carbon sequestration[86].

Increased soil productivity: The Green Revolution of the 1960s enhanced the production of grains with the development of new varieties by hybridization, as well as the provision of fertilizers and an adequate amount of irrigation[87]. There is a belief that reduced fertilizers lower the yields of production,

Scialabba and Müller-Lindenlauf[85] mentioned the reduced application of synthetic fertilizer leads to lower yields per land unit, with average yield losses in developed countries ranging from 0-20% with no significant reduction in developing countries, while improved organic manure practices have significantly showed increased yields[88]. Adhikari *et al.*[89] also found that organic fertilizers, especially vermicompost, significantly improve cabbage growth and yield in the mountainous conditions of Jumla, highlighting the positive impact of organic practices on crop productivity in the region. Likewise, the study in a hilly condition of Khotang District to evaluate different organic and inorganic fertilizers on the performances of beetroot demonstrated the substantial positive impacts of organic fertilizers like vermicompost and compost manure[90]. Many studies have been conducted to examine the efficacy of organic procedures in the mountainous part of the country, where it is proven that organic ways are more noteworthy and sustaining than synthetic procedures.

Reduction of chemical dependency: Organic amendments reduce the use of harmful agrochemicals and synthetic fertilizers, thereby lowering environmental and health risks[91]. It promotes soil health, gradual production growth and minimal pesticidal use leaving traces, ensuring food and nutritional security[92]. The balanced use of fertilizers in the rotational cropping of grain legumes like chickpeas, lentils and field peas enhanced maize productivity reducing the need for inorganic nitrogen fertilizer in the hills of Nepal according to the study of Rawal *et al.*[72]. Organic practices aim to reduce synthetic fertilizers, increase agricultural production, promote biodiversity, preserve water and trap carbon in the soil with methods like Integrated Pest Management (IPM) reducing pesticide demand, cover cropping, mulching and using N-fixing plants[93]. Thus, avoidance of chemical dependence and sustainable soil preservation as well as food crop production can be achieved via organic amendments in soil.

Local knowledge and tradition conservation: Organic farming often aligns with traditional agricultural practices in Nepal utilizing a unique blend of the natural landscape and people's inherited knowledge, particularly in those areas with limited resources[82], are increasingly adopting organic farming over the centuries, which is benefiting both domestic and export markets for livelihood improvement[51]. Indigenous practices of soil fertility management in the hills of Nepal include FYM, green manuring, *in situ* manuring, mulching, nitrogen-fixing plant cultivation, crop rotation, fallowing, terrace riser slicing, trash burning and using forest black soils[94]. These practices have been in application before the adoption of technology for soil and water conservation, which are the aspects of organic systems. So, the organic ways support indigenous techniques as it is derived from the several facets of traditional practices, thus keeping the local and traditional practices of soil conservation and agriculture.

Enhancing livelihoods of farmers: Organic practice is crucial for mountainous regions due to fragile soils, limited fertility and climate change, boosting soil health, increasing production, reducing micronutrient deficiency and sustaining rural livelihood[1]. Organic farming provides self-reliance, resource conservation, job creation, family farming, natural food, cultural preservation and climate change mitigation for future viability[82]. Banjara and Poudel[83] in their research, discovered that over 90% of their respondents were satisfied with its income, using it for child education, health facilities and house renovations from organic farming practices. It supports poor farmers in remote practising traditional agriculture on less contaminated marginal lands by connecting them to global value chains, potentially boosting their incomes, health, resilience and food security. So, the organic conservation approaches are the only easy and economical methods to sustain mountainous livelihoods, thus preserving soil properties, increasing productivity and protecting biodiversity in the long run.

CONCLUSION

Hence, the challenges in conserving soil health in mountainous regions of Nepal due to their fragile topography, steep slopes and harsh climatic conditions are compounded by land abandonment, traditional farming practices and socioeconomic constraints. However, the organic systems of farming and

soil conservation present a promising remedial solution, offering sustainable methods like crop rotation, reduced tillage, mulching, composting, green manuring and agroforestry that improve soil fertility, conserve biodiversity and mitigate environmental impacts. Besides the challenges, with the application of organic practices, Nepal can improve its agricultural productivity, conserve biodiversity and promote long-term soil conservation, all while preserving local and indigenous practices, thus enhancing the rural mountainous livelihoods. The gradual adoption of organic approaches, further bolstered by government policies, holds great potential for addressing the issues of soil erosions, land degradation and environmental challenges over the mountains of Nepal.

SIGNIFICANCE STATEMENT

The effectiveness of organic procedures for soil conservation must be acknowledged, as the mountainous part of Nepal faces the challenges of soil degradation impacting agriculture and the entire ecosystem. The mountainous inhabitants are much affected by the depleting soil health conditions that can be enhanced through biological methods, thus bolstering the farming conditions and contributing to their livelihoods and agrobiodiversity preservation. So, the organic approaches, including cover cropping, rotations, mulching, composting, green manures and reduced tillage are found to be beneficial for enhancing soil structure, nutrient cycling, reducing emissions and conserving the soil ecology, thus supporting sustainable agriculture and food security over the region.

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