Review Article

Sustainable nutrient management approaches for mountain agroecosystems

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ABSTRACT

The present paper explores the different integrated nutrient management (INM) strategies that could be implemented for mountain soil. Effective INM approaches are crucial for maintaining soil fertility, enhancing crop productivity, and ensuring sustainable agricultural practices in environments. In order to achieve the vision of world without hunger adopting INM strategies is of utmost importance as it will enhance prosperous cultivation and enabling cultivar to achieve agricultural growth, and reduce poverty. Mountain soils are often met with challenges due to their steep slopes, limited accessibility and erosion prone nature of the soil. To overcome the drawbacks INM strategies that could be implemented are terracing and contour farming, use of organic amendment to improve the soil structure, use of organic mulches to retain soil moisture and regulate soil temperature, proper selection of crop that are well suited to mountain soil and climate conditions, implementation of crop rotation to break disease and pest soil and enhance soil nutrient condition, integration of trees into agricultural landscape to promote soil conservation and enhance biodiversity, reduce soil disturbance through conservation tillage, precision application of nutrient as per the conditions of the mountain soil, and implementing measures such as contour bunds, trenches and vegetative barrier to control soil erosion. The above strategies in detail are discussed in the paper. Thus from the above strategies it could be understood that from basic practices valuable resources could be conserved but it is necessary to have utmost knowledge as to which crops to be grown in a particular environment otherwise the consequences might be deteriorating.

Keywords: Crop Rotation, Precision Agriculture, Contour Farming, Agroforestry

1. INTRODUCTION

The global population has steadily increased from over 3 billion in 1960 to more than 8 billion in recent years [1]. This growth has often led to the destruction of natural ecosystems, such as forests, alongside the advancement of agricultural areas. The United Nations projects that by 2050, we will need to provide food for 10 billion people, presenting significant challenges not only in food production but also in reducing the adverse effects of agricultural methods on the environment [2]. It may be feasible to enhance crop yields and maintain soil fertility and land productivity while limiting environmental harm through the combined application of both natural and synthetic soil nutrients [3]. In recent years, there has been a growing awareness of integrated nutrient management (INM) as a method to enhance crop yields and lower the environmental impact [4]. Numerous researchers have noted that the combined application of chemical fertilizers and organic manures holds great promise for boosting production and achieving greater stability in crop yields [5][6]. In northeastern India, many essential minerals and micronutrients in the soil become inaccessible to plants due to acidic conditions or are trapped by harmful substances. Therefore, INM may serve as an agricultural approach to convert underutilized marginal areas into productive zones, helping to achieve the strategic goal of expanding arable land, fostering an ecologically sound and economically sustainable farming system, and addressing poverty while aiming for zero hunger and ensuring food security [7]. INM aims to promote environmentally friendly practices by combining the advantageous qualities of both inorganic and organic materials. This blend can be utilized to reduce the excessive reliance on chemical fertilizers, align fertilizer usage with crop nutrient needs, preserve soil fertility, enhance yields, boost profitability, and minimize environmental pollution [8]. The growing population has placed significant pressure on the farming community to increase agricultural output. Against the backdrop of global warming, issues such as debris flow, landslides, and other severe gravitational erosion processes have intensified, resulting in diminished biological diversity, ecosystem stability, resilience, productivity, and other related factors, creating fresh challenges for conventional soil and water conservation strategies [9]. The key component of the INM goal is to reach the most effective and homogeneous combination that could lead to good management and be an effective target of the fertilizers, sufficient and balanced use of their quantity and quality, and be straightforwardly uptaken by plants for higher yield without jeopardizing soil native nutrients or polluting the environment. It is ultimately viable to achieve such a target through the wise application of integrated nutrient management (INM) approach, which is known as a balanced mixture of organic, inorganic, and bioorganic microorganisms in combinations in different practices [10]. Also, it can improve all the characteristics of molecule absorption of macronutrients (NPK) and micronutrient inputs. In addition, it can match the crop nutrient requirements and alleviate the constraints of nutrient deficiency without any harmful effects in the environment and products. In contrary, in the case of mismanagement, it always leads to soil degradation, nutrient deficiency, and quick soil runoff. In addition to water erosion occurring in mountainous regions with steep landscapes and insufficient vegetation, intense gravitational erosion is a significant contributor, particularly in the rainy season, due to the slope and the sediment source's composition. This form of erosion, driven by gravity, encompasses slips, landslides, collapses, and earth debris flows, among others. Debris flow, along with water erosion and gravitational erosion, can result in substantial damage [11]. Strategies such as enterprise diversification, crop rotation, implementing wind breaks, enhancing the number of microbial habitats, intercropping, and integrating various crop production methods are some approaches that foster stability and diversity on the farm [12]. The solution to alleviating current hardships lies in devising a strategic plan that promotes productive farming in both mountainous and flat terrain, empowering farmers to drive agricultural advancement, decrease poverty, and secure profitable returns. Both mountainous and flat soils possess distinct challenges and opportunities related to nutrient management. An integrated nutrient management approach, utilizing a minimum selective dose of well-balanced organic and inorganic fertilizers alongside specific microorganisms, can enhance nutrient availability and efficiency, thereby maintaining high yields while safeguarding the natural soil nutrients and preventing environmental pollution. Additionally, implementing integrated nutrient management can yield numerous advantages. Integrated Nutrient Management (INM) strategies serve as key tools for transforming marginal lands into productive areas. When applied to mountain soils, these strategies include practices like terracing and contour farming, which effectively reduce soil erosion and help to conserve water and nutrients. The use of organic amendments such as compost, farmyard manure, or green manures can enhance soil structure, boost water retention, and supply essential nutrients. Additionally, incorporating trees into the landscape can aid in soil conservation and promote biodiversity. Adopting minimum tillage practices reduces soil disturbance, thereby minimizing erosion and supporting overall soil health. Level terrain characterized by simple soil and heavy agricultural use necessitates

Integrated Nutrient Management (INM) strategies centered around soil testing and analysis. This process helps identify nutrient levels and pH, allowing for a more targeted nutrient application. Implementing crop rotations and intercropping legumes with cereals or other plants enhances nutrient cycling, minimizes pests and diseases, and supports biodiversity. Additionally, using precision agriculture techniques maximizes nutrient efficiency, decreases waste, and fosters sustainable farming practices. Furthermore, planting cover
enahnces contributes
crops helps to prevent soil erosion, enhance soil health, and contribute organic matter.

2. Nutrient Management strategies in Mountain Agriculture

2.1 Terracing and contour farming are effective methods for conserving soil in mountainous areas. Terracing involves constructing flat platforms on sloped terrain, while contour farming entails plowing and planting along the land's natural contours. The simplest and most fundamental method of contour tillage alters the micro-topography, enhances surface roughness, and promotes rainwater infiltration. This technique also minimizes or prevents soil erosion caused by runoff [13]. Ideally, it is applicable to land with a slope of up to 25 degrees; however, its effectiveness increases on slopes less than 20 degrees. Therefore, when practicing contour tillage, it is essential to maintain slope control within 25 degrees and consider the placement of ditches and roads to avoid
environmental stress
exacerbating water-induced erosion. To reduce entropy, autumn is an optimal time for planting. Additionally, growing crops like wheat and corn can further support soil and water conservation over a period of two to three years. In terracing, the landscape is shaped into flat 'steps,' which enhances vegetation and ground cover on slopes of 15-20 degrees, where erosion from water and gravity is most pronounced. This method slows surface runoff, increases the time and capacity for soil to absorb water, and ultimately conserves water, soil, and fertilizers, while also improving soil quality and crop yields. Terraces can be categorized into level, sloping, and slope-separated types based on various criteria. Contour hedgerow technology, often referred to as contour nitrogen-fixing plant hedge technology, utilizes nitrogen-fixing plants to support soil and water conservation efforts. This method merges agricultural and forestry practices. The benefits of nitrogen-fixing plants include (1) their ability to absorb fewer nutrients from the soil (particularly nitrogen) while increasing soil nitrogen levels, (2) their resilience to drought and ability to thrive in poor soil

conditions, (3) their effectiveness in enhancing soil quality [14], and (4) their capacity to reduce competition from other crop species, allowing for coexistence of multiple crops in the same area. The contour hedgerow system relies on plants with extensive root systems that stabilize the soil and significantly reduce soil erosion by trapping surface runoff. This technology is particularly effective on slopes exceeding 25 degrees.

2.2 The extraction of resources from mountainous areas, which holds significant potential for economic and social development, is essential. However, poor management of these activities leads to lasting negative effects even after they have ended [15]. To restore these delicate ecosystems, effective soil management is crucial, as it enhances microbial activity, improves soil structure, boosts carbon and nitrogen levels, and increases ecosystem efficiency and resilience [16]. This challenge is expected to intensify in the upcoming decades due to anticipated climate change and expanding aridity [17] [18]. Restoration initiatives can reap various benefits from increasing soil organic matter, including enhanced soil water retention, fertility, structure, and productivity [19] [20] [21] [22]. Many researchers have suggested that using organic waste amendments can effectively restore semiarid regions [23] [24] because these amendments enhance the physical, chemical, and biological properties of the soil, facilitating plant colonization and maintenance efforts [25] [26]. They also promote increased microbial activity in the soil [27 [28] and enhance carbon sequestration [29] [30].

2.3 The use of organic mulches plays a significant role in improving the soil's nutrient levels by boosting the organic matter content, which in turn enhances the physical and chemical properties of the soil [10]. The type of mulch used and the rate at which it is applied greatly influence the quantity of nutrients released and the organic matter content during the decomposition process [31]. Both soil structure and aggregate stability are essential for maintaining soil quality and nutrient availability, attributes that are positively influenced by organic mulches [32] [33]. Decomposition of the applied mulch increases soil organic matter, leading to better aggregation [34] [35]. Additionally, mulching promotes the activity of microorganisms, encourages root growth, and adds organic materials to the soil. Furthermore, mulching aids in the formation of soil aggregates and improves their stability by absorbing the impact of raindrops, enhancing surface roughness, and boosting water infiltration, which in turn reduces runoff and soil erosion [32] [36] [33] [37]. The presence of mulch also affects various biotic and abiotic soil factors, influencing pore space and connectivity [38]. Research has shown a direct relationship between the rate of mulch application and soil penetration resistance [39] [40] [38]. Increased total porosity of about 35–46% has been observed after applying mulch, which is essential for improving crop productivity. This is primarily due to enhanced soil aeration, which supports root development and nutrient uptake [38] [39]. Moreover, mulch application helps regulate soil temperature and energy levels by intercepting solar radiation, impacting the biological and chemical processes occurring within the soil [36].

2.4 Tree and grass planting for soil and water conservation (TGPSWC) is applied in regions that have experienced significant degradation of trees and grass, as well as in areas suffering from soil erosion and land desertification. This practice enhances surface vegetation cover either through natural recovery or by planting trees and grasses to mitigate erosion caused by water, wind, and gravity, thereby improving the ecological environment.

The specific benefits of Tree and grass planting for soil and water conservation TGPSWC include:

1. Grasses and branches that help prevent soil splashing and wind erosion while reducing surface runoff, with canopies capable of intercepting 10–40% of rainfall. Forest litter is effective at absorbing, storing, and allowing water to permeate; it can hold 4–6 times its own weight in water, and as it decays, it enriches the soil's physical and chemical properties. Additionally, tree roots help stabilize slopes.
2. TGPSWC positively impacts the local climate by lessening temperature fluctuations, raising humidity levels, decreasing wind speed, and improving air quality.
3. The practice also enhances economic productivity. Integrated with effective agricultural methods, tree and grass planting for soil and water conservation represents an ecological engineering

approach that emphasizes sustainable development and the responsible use of tree and grass resources.

4. In essence, TGPSWC consists of two main components: afforestation and grass planting. Afforestation primarily involves the cultivation of natural forests, shelterbelts for farmland (windbreaks), dune stabilization, beach protection, and commercial forestry. Grass plants focuses on techniques such as artificial sowing or enhancing existing grasslands while ensuring reasonable grazing practices. Furthermore, TGPSWC serves as a vital method for soil and water conservation within the broader context of managing small watersheds and operates as part of an integrated control system that aligns with the goals of technical agricultural and engineering measures for soil and water conservation [13].

2.5 Crop rotation is an essential aspect of Integrated Nutrient Management (INM) that plays a significant role in enhancing soil health and sustainability in mountain agriculture. By changing the sequence of crops grown, farmers can improve soil fertility, lessen dependency on synthetic fertilizers, and address various environmental issues [41]. When planning crop rotation, several factors should be taken into account:

1. Understanding Mountainous Conditions: Farming in mountainous areas presents distinct challenges, including steep landscapes, diverse microclimates, and particular soil types. These elements must be thoughtfully considered when developing crop rotation strategies [42].
2. Diverse Crop Selection: It's important to include a variety of crops in the rotation, especially legumes. Leguminous plants like beans and clover have the ability to fix atmospheric nitrogen in the soil, which decreases the necessity for nitrogen fertilizers [43].
3. Nutrient Cycling : Different crops have unique nutrient requirements and root depths. Alternating between deep-rooted and shallow-rooted crops allows for better access to nutrients in various soil layers, enhancing overall nutrient cycling [43].

4. Pest and Disease Management: Crop rotation helps interrupt the cycles of pests and diseases that tend to target specific crops. By rotating their crops, farmers can decrease pest and disease populations, which in turn reduce the need for pesticides [41] [43].
5. Cover Cropping: Utilizing cover crops like rye or vetch during fallow periods is beneficial. These crops can help prevent soil erosion, suppress weeds, and improve soil structure. Additionally, when incorporated back into the soil, they contribute organic matter, boosting soil fertility.
6. Long-Term Planning: It's vital to create a long-term crop rotation strategy that considers market demands, available resources on the farm, and the specific requirements of the crops intended for cultivation.
7. Monitoring and Adjustment: Regular evaluation of crop rotation results is crucial. Adjustments based on these assessments are necessary to ensure optimal effectiveness.This comprehensive approach to crop rotation can significantly enhance agricultural practices in mountainous regions.

2.6 Effective nutrient management, as part of an integrated nutrient management (INM) strategy, is essential for sustainable agriculture in mountainous regions. Precision agriculture plays a significant role in this approach by utilizing advanced technologies and data-driven methods to enhance decision-making and improve crop yields. Nutrients are the most critical and widely used inputs for plant growth. This method is particularly vital in mountainous areas, which face unique challenges such as steep terrain, varied microclimates, and nutrient-deficient soils.

2.6.1 Site-Specific Nutrient Management (SSNM) is a valuable precision agriculture technique that efficiently applies nutrients by identifying the spatial and temporal variability of nutrient levels and deficiencies in fields. The implementation of SSNM is supported by the 4R nutrient stewardship framework: 1) selecting the correct fertilizer, 2) applying it at the optimal time, 3) choosing the appropriate source, and 4) employing the right method [44].

2.6.2 Technologies such as remote sensing (including drones and satellites) and geographic information systems (GIS) allow for the assessment of crop health and nutrient levels across large areas, enabling targeted nutrient management. Machine Learning and Artificial Intelligence are utilized to analyze data from various sources, including soil sensors, weather conditions, and crop performance, to forecast nutrient requirements and fine-tune fertilizer applications. Aerial sensing leverages unmanned aerial vehicles (UAVs) and satellite imagery to evaluate and map the spatial and temporal variability of nutrient levels in fields. Ground sensing incorporates various sensors, such as electrochemical and optical devices, to assess different soil characteristics. Optical sensors utilize spectroscopy techniques, including both multispectral and hyperspectral analysis [45], to evaluate soil properties. These technologies provide rapid and cost-effective measurements while addressing labor shortages. In soil research, ground sensing has shown to be more effective than aerial sensing, yielding higher-resolution data for soil property measurements. Additionally, airborne hyperspectral sensors have demonstrated superior results in nutrient assessment when compared to satellite data [46]. The sensors are applicable in both laboratory and in-situ testing, with portable spectrometers allowing for real-time monitoring of soil properties in the field. Laboratory analyses can provide more detailed insights by collecting spectra from soil samples to investigate the relationships between reflectance spectra and soil characteristics.

2.7 Incorporating trees into mountain agricultural practices, a method known as agroforestry, is an essential strategy for enhancing soil health and promoting sustainability. This approach improves soil fertility, water retention, and biodiversity, providing a variety of ecological, economic, and social advantages. Agroforestry combines the cultivation of trees with crops and/or livestock, leading to a more resilient and efficient land-use system [47]. Trees serve as natural nutrient sources, retrieving minerals from deeper soil levels and replenishing surface nutrients through leaf litter and decomposition, which reduces reliance on synthetic fertilizers. The root systems of trees help anchor the soil, minimizing erosion from wind and water-a critical factor in mountainous areas that experience steep slopes and heavy rainfall. Tree canopies catch rainfall, softening its impact on the soil and allowing for greater water absorption, which aids groundwater recharge and increases water availability for agricultural use. The organic matter from decomposing leaves, branches, and roots enhances soil structure, improving porosity and the soil's ability to retain water. Agroforestry creates diverse habitats that support a variety of beneficial soil organisms, including microbes essential for nutrient cycling and overall soil vitality. Additionally, trees capture carbon from the atmosphere, assisting in the reduction of greenhouse gas emissions and helping combat climate change [48]. Examples of agroforestry practices in mountainous areas include contour hedgerows, where trees are planted along slopes to control erosion and improve water absorption; alley cropping, where trees are arranged in rows with crops grown in the spaces in between; and silvopastoral systems, which integrate trees with grazing livestock to provide animal fodder and enhance soil health through manure deposition, all while alleviating grazing pressure on sensitive regions [48]. By implementing tree integration in mountain farming, farmers can boost soil health, increase productivity, and enhance their livelihoods while also supporting environmental sustainability [48].

3. Conclusion

Nutrient Management strategies are crucial for maintaining soil fertility, promoting sustainable agriculture, and ensuring ecosystem services in mountain soils. By understanding the unique challenges and opportunities associated with the environment, farmers and researcher can develop and implement effective practices that benefit both the environment and agricultural productivity.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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