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Research Article

A case study on terracing and mulching in Namangan region hills located in Uzbekistan

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Abstract
Soil erosion and fertility decline pose a significant challenge to sustainable agriculture in the hilly regions of Namangan in Uzbekistan (Central Asia). This study investigates the long-term effects of terracing and mulching on soil fertility and stability from 2013 to 2023. Terracing involves converting steep slopes into stepped fields to reduce runoff, while mulching involves applying organic or inorganic materials to retain moisture and improve nutrient availability. Soil samples were taken annually from two depths (0–30 cm and 31–50 cm) and analysed for key fertility indicators. The results show a significant increase in the humus content in the 0–30 cm layer, which rose from 0.3 % in the untreated areas to 1.0 % with mulch and terracing. The phosphorus content increased significantly, reaching 83.7 mg/kg in the terraced and mulched soils, compared to 11.2 mg/kg in the untreated soils. The potassium content also improved: the treated soils contained 260 mg/kg compared to 94 mg/kg in the untreated plots. These results underline the effectiveness of terracing and mulching in improving soil health and stability through better nutrient retention and reduced erosion. The study underscores the potential of these sustainable practices to promote long-term agricultural productivity in erosion-prone regions.

Keywords: Mulching, Soil erosion, Soil fertility, Sustainable agriculture, Terracing

INTRODUCTION

Soil degradation is a critical challenge to sustainable agriculture, threatening food security and environmental health worldwide (Juraev and Ahn, 2023). Soil erosion, a major aspect of this problem, is exacerbated by inappropriate agricultural practices and climatic changes. This erosion not only reduces the productive capacity of the soil but also leads to the loss of vital organic matter and nutrients, adversely affecting soil fertility (Siebert *et al*., 2010; Parsons, 2019). Various management strategies have been introduced to combat soil erosion, notably terracing and mulching. Terracing is the process of converting steeply sloping land into a series of steps to reduce runoff and significantly reduce erosion. Mulching involves covering the soil with organic or inorganic materials to retain moisture, suppress weed growth and increase fertility (Pandey *et al*. 2016). Despite their effectiveness, these methods have weaknesses: terracing is labour-intensive and may not be profitable for smaller farms, while mulching requires continuous replenishment and may not provide adequate erosion control on steeper slopes (Bhargavi and Anusha, 2023).

Terracing and mulching have been extensively studied for their positive effects on soil fertility and erosion control. These techniques are crucial for sustainable agriculture, especially in regions threatened by soil degradation (Shi *et al*. 2009). Terracing reduces surface runoff and soil erosion, improving water retention and nutrient availability (Liu *et al*. 2021). Mulching preserves moisture, reduces weed growth and enhances nutrient cycling, thereby maintaining soil health and increasing agricultural productivity (Akhtar *et al*., 2019).

Several studies highlight the benefits of these practices. Akhtar *et al*. (2019) reported that combining mulching with nitrogen fertilizer significantly boosts soil enzyme activities and increases the availability of essential nutrients such as nitrogen, phosphorus, and potassium. Shi *et al*. (2009) found that long-term use of mulch, particularly when combined with organic manures and chemical fertilizers, enhances soil organic matter and nutrient status. Han *et al*. (2014) and Gill *et al*. (2022) showed that mulching in orchards significantly increases the content of soil organic matter and available nutrients in the topsoil. Additionally, Ravichandran *et al*. (2022) emphasized that mulching effectively conserves soil moisture by reducing evaporation rates, which is crucial in arid and semi-arid regions.

However, gaps remain in understanding the combined long-term effects of terracing and mulching across different environmental conditions. The present study builds on existing research by exploring the synergistic effects of terracing and mulching on soil health in the Namangan region. This study sought to investigate the combined effects of these agricultural technologies on soil fertility and erosion control in the hilly areas of Namangan, focusing on changes in humus content and levels of key macroelements- phosphorus and potassium as indicators of improved soil health.

MATERIALS AND METHODS

Study area

The study was conducted in the Namangan region, located in the south-eastern foothills of the Kurama and Chotkal Mountains in the city of Namangan, Uzbekistan. The approximate geographical coordinates are 40.9983° N and 71.6726° E. This area features a diverse topography that transitions from steep mountainous zones with inclines of 45-50 degrees to more moderate slopes of 15-20 degrees and gentle slopes of 3-10 degrees in hilly areas. The terrain flattens as it approaches the Syrdarya River, characterized by deflationary plains. Experimental sites were selected based on their varied topographical characteristics, which are representative of the broader region. These sites included areas with minimal slopes of 0-3 degrees, where irrigation erosion risks are low, and areas with steep slopes ranging from 5-10 degrees, where specialized agrotechnical interventions are necessary due to the high erosion risk.

The agrotechnologies employed included terracing and mulching. Terracing was used to convert steep slopes into terraced fields to reduce runoff and soil erosion. Mulching involved applying organic materials like leaf litter, straw, peat and inorganic materials like plastic films to conserve soil moisture and improve soil structure.

The experimental setup began in 2013 with several phases:

1. Initial setup (2013): Terracing and organic mulching were first implemented on a 500 m² area within the Uychi Sohibkor Bustoni agricultural company. Each seedling was surrounded by cellophane to prevent moisture loss, covered by 3-5 cm of soil to moderate soil temperature, and encircled with a 30 cm deep trench to capture rainwater.

2. Expansion and continued experimentation (2014-2017): The experimental area was expanded following positive initial results,. Terracing and mulching were continuously applied, and the effects were monitored and compared with control (non-mulched) areas.

3. Advanced implementation (2017): A new experimental park was established, enhancing the precision of agrotechnological applications on a 0.3-hectare area. Fruit seedlings were systematically planted and terraced to a 50 cm radius to maximize water retention and soil stability.

4. Long-term monitoring (2013-2023): Soil samples were taken annually to assess changes in soil humus content, phosphorus, and potassium levels. Samples were collected from depths of 0-30 cm and 31-50 cm, air-dried, finely ground, and sieved for laboratory analysis conducted at the Namangan branch of the Agrochemical Station.

Statistical analysis

Statistical analyses were conducted to evaluate the effectiveness of the agrotechnologies. Soil nutrient data were classified according to standard categories for phosphorus and potassium content, and changes over time were analyzed using repeated measures ANOVA to determine the significance of the interventions, with confidence levels set at 95%. The methodology for assessing the long-term effects of terracing and mulching on soil health in hilly agricultural areas is thorough, but measurements of the effectiveness of terraces in water harvesting are lacking. This approach ensures reproducibility and provides findings that apply to similar landscapes worldwide.

Geography and agriculture of Namangan

Namangan region is situated in the southeastern foothills of the Kurama and Chotkol mountains (Fig. 1). The terrain descends from the mountain peaks towards the

Fig. 1. *Map of Uzbekistan showing study area: Namangan region*

Table 1. Average slope of Namangan region relief

No.	Slope Level (In degrees)	Territory (Thousand hectares)	As a Percentage of the Total Area (%)
1	0 – 1	180	24
2	1 – 3	150	20
3	3 – 5	200	27
4	5 – 7	70	9
5	7 – 10	45	6
6	10 – 15	80	11
7	15	20	3
Total		740	100

Syrdarya River, transitioning through rolling hills at the valley's edge. The terrain near the Syrdarya River is predominantly flat, characterized by deflationary plains. The regional distribution based on the slope of the terrain is detailed in Table 1.If you look at the data in Table 2, you will notice that 44% of the Namangan region consists of plains with minimum slopes of 0-3 degrees. In such terrains, the risk of irrigation erosion is markedly low, negating the need for extensive water erosion control measures. This is attributed to findings that areas with 1-3 degrees slopes are largely resistant to irrigation erosion, with only isolated instances of partial erosion.

Adjacent to the western Tianshan mountain range, the hilly regions of Namangan are categorized into three elevation bands: low, medium, and high hills, with heights up to 1600 meters. Consequently, the hill regions of Namangan are differentiated into low, medium, and high zones, each characterized by similar slope gradients. Specifically, low hills typically feature steep gradients of 3-5 degrees and account for 27% of the regional territory. Mid-height hills exhibit slopes of 5-7 degrees, and high hills range from 7-10 degrees, collectively comprising 15% of the area. Overall, the hills, along with the pre-hill and post-hill sloping plains, constitute 32% of the region, roughly one-third.

Much of Namangan's irrigated land is situated on low hills with 3-5 degrees slopes, including the plains that precede and follow these hills. The lands on such slopes are prone to significant irrigation erosion, result-

No.	Districts	Irrigated land, thousand ha (as of 2022)	Erosion in irrigation			Lands subject to total irrigation erosion
			Weak	Middle	Strong	
1	Mingbulok	38190	-	-	-	-
2	Kosonsoy	25206	8100	1729	1773	11602
3	Namangan	21748	1980	1370	680	4030
4	Norin	16938	8000	1220	800	10020
5	Pop	40659	13780	5630	2650	22060
6	Turakurgan	19035	5940	3760	1760	11460
7	Uychi	20513	1867	402	500	2769
8	Uchkurgan	24103	6300	3910	1220	11430
9	Chortok	20357	15300	2800	1500	19600
10	Chust	33942	7980	3050	4760	15790
11	Yangiqkurgan	27837	10210	5600	6000	21800
Total		288528	79457	29471	21643	130561

ing in moderate erosion across these extensive agricultural areas. For medium and high hill areas, where slopes range from 5-10 degrees, specialized agrotechnical interventions are imperative to manage soil erosion in irrigated agriculture. These steeper slopes are particularly vulnerable to irrigation erosion. Specific areas within the Namangan region affected by irrigation erosion are also documented in Table 2.

The data presented in Table 2 elucidates that irrigation erosion is a significant concern in the Namangan region, with over 130,000 hectares — 45% of the region's total irrigated lands—being adversely affected. Predominantly, this erosion impacts the districts of Pop, Yangikurgan, Chortoq, and Kosonsoy, which host the majority of the hilly, irrigated terrains (Fig. 1). It is estimated that 60-65% of the irrigated hill soils have undergone varying degrees of erosion.

A considerable portion, approximately 70%, of Namangan's irrigated land is located within these hilly areas. The inherent characteristics of these hills, including the superficial fertile soil layer, which was measured only 15-20 cm. in depth, and their predominantly granular composition of sand, silt, and gravel, facilitate both water permeability and impermeability. This composition, coupled with the cultivation of water-intensive crops, exacerbates severe irrigation erosion and contributes to broader geo-ecological challenges.

In the hilly region, where loess and loess-like deposits are prevalent, irrigation erosion initiates when the slope exceeds 2 degrees and intensifies markedly at slopes greater than 3.5 degrees. The steep inclines ranging from 3 to 10 degrees that characterize most of the hills further predispose these areas to widespread soil erosion.

To understand the dynamics of irrigation erosion, the researchers focused on the northeastern hills of Namangan. The observations show that all forms of irrigation erosion are widespread, with surface and longitudinal erosion particularly pronounced (Chathuranika *et al*., 2022). This study shows that about 80 % of irrigated hill areas are affected by erosion, mainly surface erosion (Saparov *et al*., 2013). Interestingly, erosion is less noticeable on flat terrain and in depressions where slopes are minimal, and in some areas, there is even an accumulation and thickening of fertile soil layers in depressions and lower levels (Chathuranika *et al*., 2023).

Historically, the opening of the Great Namangan Canal in 1975 marked a significant development phase for the mountainous areas and promoted extensive agricultural activities. Irrigated agriculture intensified increasingly since its introduction and expansion until the 1980s. In the 43 years that followed, the effects of erosion from irrigation became clearly visible, highlighting the ongoing and evolving challenge of managing soil integrity in these cultivated plateaus (Fig. 2). This historical context underscores the enduring nature of irrigation erosion challenges in the Namangan region and highlights the need for continued and innovative soil management practices to mitigate these effects.

The effect of irrigation on soil erosion is clearly noticeable across different elevations in the Namangan region. Studies in the northeastern hill country of the Namangan region in Uzbekistan have shown that the fertile

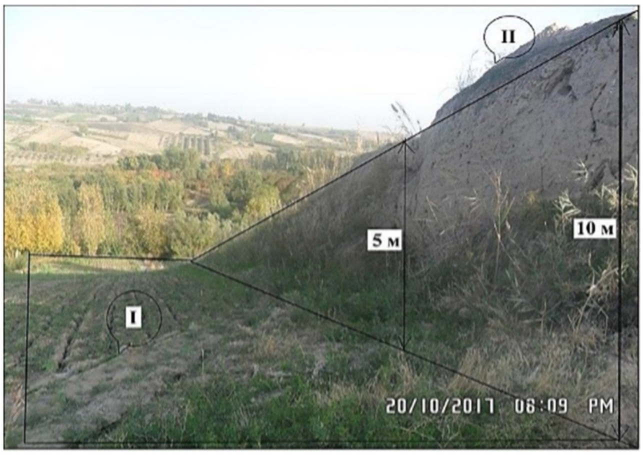

Fig. 2. *Erosion from surface irrigation in Hilly agriculture (Namangan, Uzbekistan) (I) 43-Year Irrigated Area, (II) Non-irrigated area*

Fig. 3. *Surface erosion revealing gravel layers in Irrigated hilly farmlands (2017; Namangan, Uzbekistan)*

surface layers, which are up to 10 meters thick at the highest points of the slopes and even more in some areas, are heavily eroded. The middle sections of the slopes show a soil loss of about 5 meters, while the lower sections show losses of 0.5 to 1 meter due to the effects of irrigation water (Chathuranika *et al*., 2022). The erosive processes have particularly affected large hilly terrains where gravel layers, typically found at depths of 0.5 to 1.5 meters, are now exposed as the fertile topsoil is washed away. This exposure of gravel layers due to irrigation erosion has multiple adverse consequences for agricultural practices (Fig. 3).

Firstly, it makes agronomic work considerably more difficult, as working with gravelly soils is much more difficult than with cohesive soil types. Secondly, the hydraulic properties of these gravel layers are suboptimal- they have a low water retention capacity and a high infiltration rate, which leads to increased water requirements for crop irrigation. Thirdly, the prevalence of salt marshes and saline soils in these areas is due to the fact that irrigation water percolates quickly through the gravel, facilitating the rise of saline water from the underlying layers to the surface. This phenomenon is particularly noticeable on the lower slopes where the gravel layer is closer to the surface and exacerbates the salinization of the soil.

It is important to recognize that while natural phenomena such as hailstorms and wind contribute to soil erosion in hilly regions, irrigation erosion presents a more formidable challenge. The data clearly illustrate that irrigation practices lead to significant erosion of the surface fertile layer, along with vital micro and macronutrients and humus. Various agronomic strategies have been researched and implemented to counteract this degradation and increase soil fertility. These include terracing, which reduces runoff and erosion while improving water retention and nutrient availability (Liu *et al*., 2021), and mulching, which conserves moisture, suppresses weed growth and promotes nutrient cycling (Shi *et al*., 2009). Other strategies such as contour hedges (Shi *et al*., 2009), crop rotations to improve soil structure (Costantini *et al*., 2018), the use of organic fertilisers such as compost (Akhtar *et al*., 2019) and improved irrigation techniques to minimise erosion (Isaev *et al*., 2023) have also been shown to be very effective in maintaining soil health.

Effective agrotechnical measures include terracing and mulching. These methods are designed to prevent the loss of soil components and improve the nutrient profile of the soil. Terracing involves altering the physical landscape to reduce runoff and erosion, while mulching involves applying a protective layer of organic materials such as leaf litter, straw or peat or inorganic materials such as plastic sheeting - around crops. This mulch layer minimizes water evaporation and suppresses weed growth, thereby conserving soil moisture and improving soil structure (Fig. 4). In fact, the term "mulch" itself likely originates from the German word "molsch", meaning to cover the soil around plants with materials that decompose gradually, contributing to soil health and fertility. This etymology underscores the practice's long-standing use in agriculture and its role in sustainable soil management.

Fig. 4. *(1) organic mulching; (2) plastic mulching*

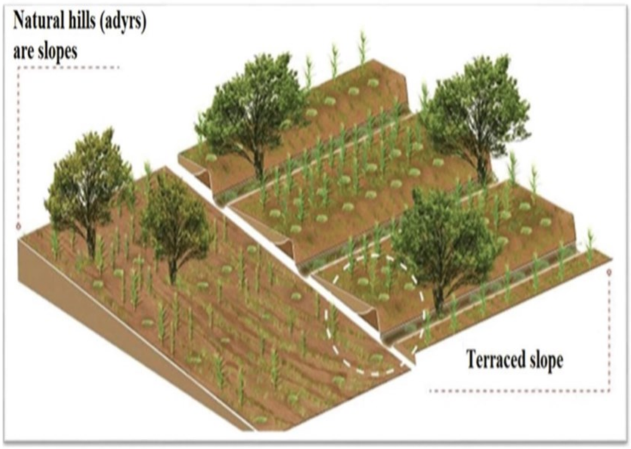

Fig. 5. *Natural vs. Terraced hill slope*

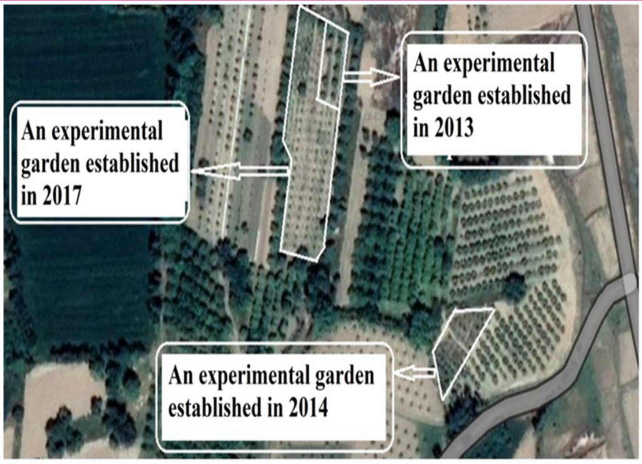

Fig. 6. *A space photo of the experimental areas*

Terracing involves engineering mountainous and hilly terrains into step-like formations to mitigate erosion and runoff (Fig. 5). In regions characterized by steep slopes, significant precipitation, specifically 60-70% of spring rains, was lost to runoff. This process strips away the fertile topsoil and drastically reduces soil moisture content, compromising agricultural viability. The implementation of terracing is strategically designed to curtail these challenges. By converting the natural slope into terraced steps, water retention is significantly improved and water flow rate over the soil surface is reduced. Consequently, terracing promotes the retention and gradual absorption of moisture, preventing both the runoff of important nutrients and the erosion of the fertile soil layer. This method proves to be essential for maintaining soil fertility and increasing agricultural productivity in regions with steep slopes.

In 2013, 2014, and 2017, a series of dry gardens were established in the Uychti district's hilly areas of the Namangan region, utilizing the agrotechnologies of mulching and terracing as previously detailed. These initiatives exemplify the practical application of these technologies in promoting sustainable agriculture in arid and semi-arid environments.

The first experimental work was carried out in 2013 at the "Uychi Sohibkor Bustoni" farm, located in the Namangan region's north-eastern hills, more precisely in the northern part of the Uychti district. This site, which is characterized by its hilly terrain, lies between 500 and 550 meters above sea level. The pilot project commenced with the allocation of 500 square meters of land for the garden (Fig. 6). In March, a variety of fruit seedlings were planted, and to mitigate moisture loss, each was encircled with cellophane, extending 80-100 cm. in radius. The cellophane was covered with a soil layer approximately 3-5 centimetres thick to further ensure moisture retention and regulate soil temperature. In addition, a 30 cm deep trench was dug around the perimeter of the cellophane to facilitate the collection of rainwater and increase soil moisture, optimizing the microclimate for the seedlings (Fig. 7). This methodological approach emphasizes the integration of traditional agricultural techniques with innovative practices to improve water efficiency and soil conservation in hilly agricultural areas.

Experimental activities were extended into 2014, continuing the use of plastic mulching agrotechnology, which had been successfully implemented the previous year. Encouraged by the positive outcomes observed in 2013, a new experimental site was delineated adjacent to the original plot, covering an additional 500 square meters (Fig. 8). This extension also investigated the reproducibility and effectiveness of plastic mulching techniques under similar environmental conditions, providing a broader basis for evaluating the impact of the technology on soil moisture conservation and plant growth.

Since 2016, the experimental area has incorporated the agrotechnology of terracing alongside mulching, employing a novel approach termed the "lunar" method. This technique involves sculpting the mulched area around fruit seedlings into a series of small, moon-shaped terraces, each approximately 1 meter in radius. The terrace surfaces were carefully smoothed and compacted to improve structural integrity. Sheets 1 to

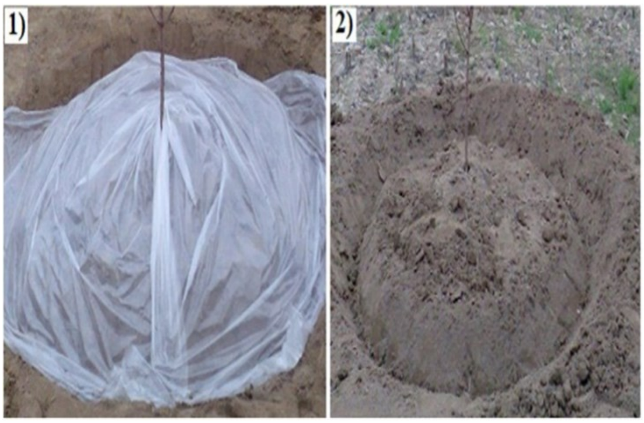

Fig. 7. *(1) Mulching experimental seedlings with film, (2) Soil covering and Border ditch formation*

Fig. 8. *Plastic mulching process for fruit seedlings (Experimental area, 2014)*

Fig. 9. *Slope terracing, rain collection, mulching, and humus enrichment for seedlings*

1.5 meters long and 1.5 to 2 meters wide were strategically placed over these terraced areas to further optimize water management. This installation was designed to channel rainwater directly onto the terraced areas, preventing it from infiltrating directly into the ground and instead allowing a controlled flow of water across the terraced landscape (Fig. 9). The sheets were laid at the beginning of the rainy season in early March. They were removed in early May, coinciding with the end of the rainy season, to maximize water absorption and minimize soil erosion.

In November 2017, an expansion of the research initiative led to the establishment of a new trial park adjacent to the existing trial areas. This latest expansion, which covers an area of 0.3 hectares (Fig. 10), was designed to apply a refined and optimized experimental methodology. Distinct from its predecessors, this garden was structured to enhance the precision of agrotechnological applications.

In the initial phase, a large number of fruit seedlings were introduced into the garden and systematically planted in a 3x3 meter arrangement. A key innovation in this phase was the creation of terraces within a radius of 50 cm around each seedling to improve water retention and soil stability in the immediate vicinity of the plants (Fig. 10). This adaptation represents a targeted approach to maximize the micro-environmental conditions essential for seedling growth and sustainability, and highlights a continuous evolution and improvement of the experimental techniques used in these studies.

Beginning in late winter and continuing into the early spring of 2019, an enhanced mulching protocol was implemented for the experimental seedlings using organic materials. Initially, during the final months of winter, a layer of humus approximately 3-5 cm thick was applied to both the terraced and previously mowed surfaces (Fig. 10). This application of organic mulch was strategically timed to coincide with the seasonal transition, optimizing soil conditions to support emerging plant growth by improving moisture retention and adding vital organic nutrients to the soil.

In early spring 2019, a refined mulching protocol was implemented involving placing a 3-5 cm layer of plant leaves over the humus manure surrounding the seedlings (Fig. 11). This layer of foliage provided crucial protection against direct sunlight and wind, thereby preserving the moisture accumulated over the winter. Additionally, this arrangement enhanced the soil's capacity to absorb rainwater throughout the spring season.

Following the cessation of spring rainfall in mid-May, a secondary layer of plastic mulching was applied. This involved placing plastic films directly over the leaf layer, which were then covered with a 3-5 cm layer of soil. This strategy effectively retained the moisture accumulated during the winter and spring, ensuring it remained available for the fruit seedlings' growth. By September, the plastic films were removed, and the underlying humus was integrated with additional manure and leaf litter, marking the completion of the scheduled experimental activities for that season.

In 2023, a systematic evaluation of the terracing and mulching efforts was conducted to assess changes in soil productivity. This evaluation involved comprehensive laboratory analysis focused on the soil's humus, phosphorus, and potassium content. Soil samples were collected using a detailed stratified method from 0-30 cm depths and 31-50 cm. Approximately 300-400 grams of each sample was taken sequentially from the soil profile's lower to upper layers.

The sampling procedure was meticulous as each soil sample was cut from the center of the specified layer, placed on thick paper, and labelled with detailed information, including the depth, geographical data, and sampling date. These samples were then air-dried, finely ground using a mortar and pestle, and passed through a 1 mm mesh sieve. Non-sieved, stony por-

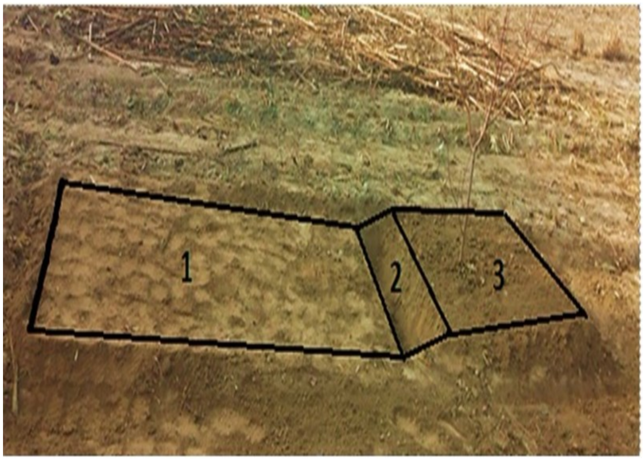

Fig. 10. *Rain-capturing terracing process: 1)Smoothed Surface for Channeling Rainwater; Rainwater Collection Trench;3) Terraced Surface*

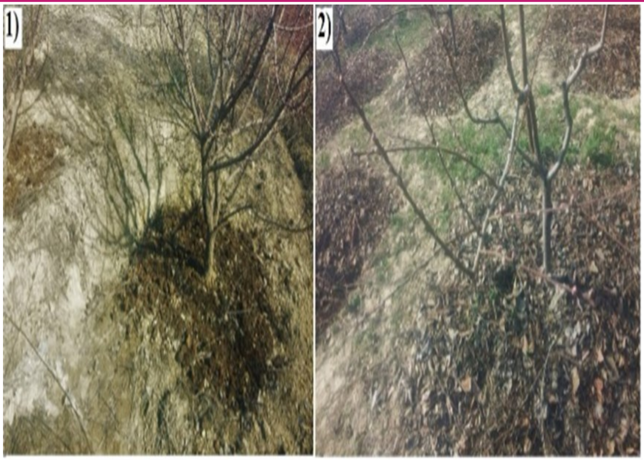

Fig. 11. *Terracing and mulching:1)Compost application on terraced soil;2) Mulching with plant leaves over humus*

tions were washed, dried, and weighed to quantify the skeletal fraction of the soil. Finally, the processed soil samples were prepared for detailed laboratory analysis, which was conducted at the laboratory of the Namangan branch of the Agrochemical Station. This comprehensive approach ensured the integrity of the data and supported the objective evaluation of the agrotechnological interventions' impact on soil health and productivity.

RESULTS

The results from Table 3 highlight a significant increase in soil humus content due to the application of mulching and terracing agrotechnologies. In the 0-30 cm soil layer, humus content in organically mulched areas increased from 0.3% in 2013 to 1.0% in 2023, representing a substantial improvement of 0.7% over the decade. Conversely, the 30-50 cm layer showed no change, maintaining a humus level of 0.4%, indicating that the impact of these technologies is more pronounced in the upper soil layers. Subsequent implementations in 2014 and 2017 further demonstrated incremental increases in humus content. By 2014, the combined application of terracing and mulching resulted in a humus content increase to 0.4% in the 0–30 cm soil layer, showing a slight improvement compared to non-mulched soils. By 2017, the humus content in this layer further increased to 1.0%, demonstrating the sustained effectiveness of these agrotechnologies in en-

Table 3. Impact of terracing and mulching on soil humus content (Lab Analyses, 2023)

Year of the experiment based on terracing and mulching	Measurement options	Depth of the soil layer, cm	Amount of humus, %
2013	Not mulched	0-30	0,3
		30-50	0,4
	Organically mulched	0-30	1,0
		30-50	0,4
2014	Not mulched	0-30	0,3
		30-50	0,1
	Terraced and organically mulched	0-30	0,4
		30-50	0,1
2017	Organically mulched	0-30	1,0
		30-50	0,5
	Plastic mulched	0-30	1,0
		30-50	0,5
	Not mulched	0-30	0,8
		30-50	0,5

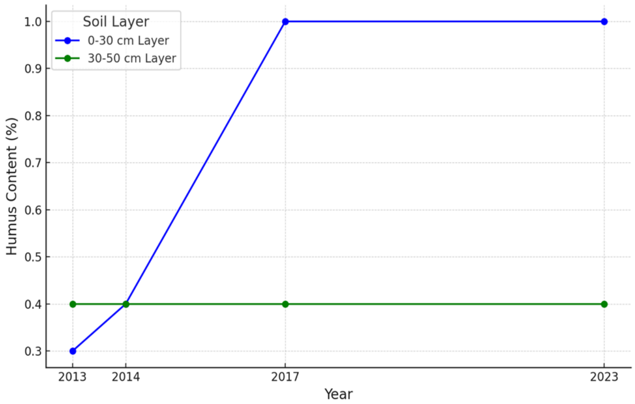

Fig. 12. *Change in soil humus content over time* (2013-2023); *Illustrates the effects of mulching and terracing on the humus content in two soil layers: 0-30 cm and 30-50 cm. The data shows a significant increase in humus content in the 0-30 cm layer from 0.3% in 2013 to 1.0% in 2023. No change is observed in the 30-50 cm layer, which remains at 0.4%*

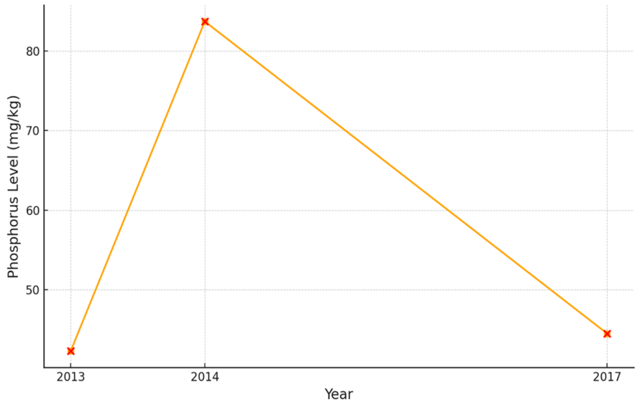

Fig. 13. *Phosphorus levels in organically mulched soils (2013-2017); Showing the increase in phosphorus content in organically mulched soils from 42.3 mg/kg in 2013 to a peak value of 83.7 mg/kg in 2014, which is attributable to mulching and terracing. By 2017, the value had stabilized at 44.5 mg/kg in the 0-30 cm thick* soil layer

hancing soil organic matter over time (Fig. 12).

Statistical analysis using ANOVA indicated significant differences ($p < 0.05$) in humus content between the different treatments and years, particularly in the 0-30 cm soil layer.

The effects of terracing and mulching on key soil microelement-phosphorus and potassium were significant, as detailed in Table 4. Phosphorus levels in organically mulched soils reached a medium level of 42.3 mg/kg in 2013, substantially increasing from the very low levels found in non-mulched soils. By 2014, these levels had escalated to a very high 83.7 mg/kg in terraced and mulched soils, starkly contrasting with the lower levels in non-mulched areas. In 2017, further positive results were observed, with phosphorus levels in the 0-30 cm layer of organically mulched soil aligning with the average standard at 44.5 mg/kg despite lower levels observed in plastic mulched soils (Fig. 13).

Potassium levels displayed variability over the years. In 2013, the amount of potassium in organically mulched soil was below the average but significantly improved over the non-mulched soil. However, no significant changes in potassium levels were noted in 2014 across all experimental conditions, suggesting that initial gains may have stabilized. By 2017, a noticeable improvement was again recorded, with potassium levels in organically mulched soil reaching the average standard of 260 mg/kg (Fig. 14).

DISCUSSION

The results of the present study emphasised the significant and differential effects of terracing and mulching on soil fertility, particularly in the enrichment of key nutrients such as *phosphorus* (P) and *potassium* (K), which are critical for plant health and productivity. These results are consistent with global evidence of the effectiveness of these practices, although different results are observed due to regional differences in soil types, climatic conditions and management practices.

The observed increase in humus content in the 0–30 cm soil layer from 0.3% in the untreated areas to 1.0% in the treated areas reflects the long-term benefits of terracing and mulching. Similar improvements in soil organic matter have been reported on the Loess Plateau in China, where mulching combined with nitrogen fertilisation increased soil organic carbon, nitrogen and phosphorus content (Chen *et al*., 2021; Zhang *et al*., 2023). However, our results showed slower nutrient accumulation in deeper soil layers, a trend consistent with studies on loamy and clayey soils, which suggest that the decomposition and downward migration of organic matter are influenced by soil texture and climatic conditions (Cheng *et al*., 2020; Hao *et al*., 2023).

The phosphorus content in the treated soils increased significantly, reaching 83.7 mg/kg compared to 11.2 mg/kg in untreated soils. These results are in line with the findings of Akhtar *et al*. (2019), where straw mulch increased phosphorus availability by 45% in semi-arid regions. Similarly, Zhang *et al*. (2023) reported that balanced fertilisation with straw mulch significantly improved the available phosphorus content in purple soils. In contrast, studies on rice paddy terraces in China have highlighted the role of organic amendments in improving phosphorus content and emphasised the importance of compost and manure applications (Chen *et al*., 2021). These differences highlight the need for tailored nutrient management strategies to optimise phosphorus availability under different soil and climatic conditions.

Potassium levels in treated soils increased from 94 mg/kg in untreated soils to 260 mg/kg, confirming the posi-

Table 4. Impact of terracing and mulching agrotechnologies on soil phosphorus & potassium (Lab Analyses, 2023)

Year of the experiment based on terracing and mulching	Measurement options	Depth of the soil layer, cm	Phosphorus, mg/kg	Potassium, mg/kg
2013	Not mulched	0-30	11,2	94
		30-50	12,3	125
	Organically mulched	0-30	42,3	159
		30-50	6,1	92
2014	Not mulched	0-30	24,1	104
		30-50	7,7	64
	Terraced and organically mulched	0-30	83,7	86
		30-50	13,0	72
2017	Organically mulched	0-30	44,5	260
		30-50	6,1	106
	Plastic mulched	0-30	20,3	108
		30-50	9,5	96
	Not mulched	0-30	16,6	123
		30-50	9,5	105

tive effects of mulching and terracing on nutrient fixation. Comparable improvements were observed in regions such as the Loess Plateau, where long-term mulching practises such as straw or ridge-film mulching increased available potassium concentrations and improved crop productivity (e.g., Chen *et al*., 2021; Hao *et al*., 2023). However, the variation in potassium content across years in our study suggests that external factors such as rainfall variability and initial soil conditions play an important role, which warrants further investigation.

Despite these promising results, there are still important limitations. The lack of hydrological data on water retention by terracing is a critical gap, as the main purpose of terracing is to improve water retention and reduce runoff. Future studies should incorporate hydrological assessments to quantify these benefits and their impact on soil moisture and crop yields. Similar gaps have been addressed in studies on rice paddy terraces, where water management practises have been shown to improve soil quality and agricultural productivity (Chen *et al*., 2021).

Another limitation is the lack of detailed soil characterisation in the experimental plots. Understanding soil texture, pH and organic content is essential for contextualising the results and comparing them with other studies; for example, the weatherability of loess soils in the Gansu region of China has been shown to influence potassium availability, emphasising the importance of soil type in determining nutrient dynamics (e.g., Chen *et al*., 2021). Comprehensive soil profiling in future research will enable a more robust assessment of the wider applicability of these agrotechnical practises.

The results of this study are consistent with broader research demonstrating the benefits of terracing and mulching in improving soil health. For example, Liao *et al*. (2021) found that mulching increased organic matter, nitrogen and available phosphorus content in orchard soils while reducing the need for irrigation water. Similarly, Chen *et al*. (2021) reported that combining straw mulch with high nitrogen fertilisation improved soil enzyme activities, microbial communities, and nutrient availability, resulting in higher soil quality indices. However, the slower nutrient changes in deeper soil layers observed in our study suggest that the benefits of mulching and terracing are more pronounced in the surface soils, possibly due to less migration of organic matter in compacted or less permeable soils.

The results have both theoretical and practical implications. Theoretically, they underpin the soil fertility management framework, favouring organic matter integration into agricultural practices to maintain soil health. In practice, they support the adoption of terracing and mulching as effective agrotechnical strategies for sus-

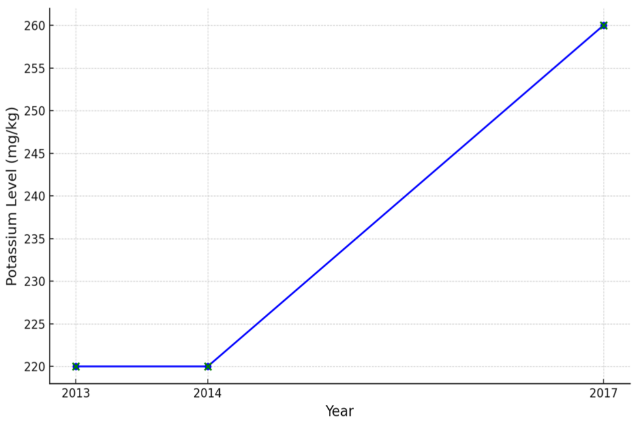

Fig. 14. *Potassium levels in organically mulched soils (2013-2017);Illustrating the variability of potassium content in organically mulched soils. While no significant changes were observed in 2014, the potassium content improved from a below-average value (220 mg/kg in 2013) to the standard value of 260 mg/kg in 2017*

tainable agriculture, especially in erosion-prone regions. As demonstrated in this study, long-term applications can significantly improve soil resilience and agricultural productivity.

So, while this study confirms the benefits of terracing and mulching, further research is needed to fill the gaps identified, such as the lack of hydrological data and detailed soil characterisation. In addition, research into complementary practices such as crop rotation and advanced mulching materials could optimise these strategies for wider application. This research provides a solid foundation for sustainable soil management and emphasises the crucial role of tailored measures in mitigating soil degradation and improving agricultural sustainability.

Conclusion

This study showed that the combined use of terracing and mulching significantly improved soil fertility and stability in the Namangan region of Uzbekistan. Within a decade, the humus content in the upper –soil layer increased from 0.3 % to 1.0 %, the phosphorus content to 83.7 mg/kg and the potassium content to 260 mg/kg. Terracing effectively reduced runoff and retained nutrients on steep slopes, while mulching ensured long-term organic matter enrichment and moisture conservation.The decade-long evaluation of integrated soil management practices in a topographically challenging region provided solid evidence of their ability to mitigate soil erosion and improve fertility. The results provide a reproducible model for sustainable agricultural practices in hilly terrain with similar environmental and soil conditions. Future studies should focus on quantifying the hydrological benefits of terracing, particularly in terms of water harvesting and effects on crop productivity. In addition, detailed characterisation of soil types and research into complementary practices such as tailored mulching materials and advanced irrigation techniques could further optimise these strategies for wider application.

Conflict of interest

The authors declare that they have no conflict of interest.

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