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Rainfall Simulation for Estimation of Soil and Nutrient Losses under Different Cropping Systems

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Soil erosion and sediment loss are a serious threat to crop production and the environment. A study was conducted to quantify the loss of soil sediment and associated nutrients under different cropping systems using rainfall simulation. Sediment and nutrient losses and runoff water were assessed using the runoff-plot technique in the research field of the National Maize Research Programme (NMRP) and farms of Agriculture and Forestry University (AFU), Rampur, Chitwan, Nepal, during early spring 2022. Twenty-four initial soil samples were collected from the topsoil of the experimental sites to determine the initial nutrient status of the soil. Rainfall was then simulated for approximately half an hour at an intensity of 58±3 mm hr^{-1} from a height of 5 m above the ground. Runoff samples and sediments were collected from a 0.5936 m^2 runoff plot and analysed for nutrient loss in the laboratories. The highest runoff flow (147 thousand Liter ha^{-1}) and the highest sediment loss was observed under recently tilled vegetable field with exposed soil (842.3 kg ha^{-1}) and the lowest in fallow land (12.3 kg ha^{-1}). Also, the exposed plot had the highest amounts of nitrogen (N) and potassium (K) eroded: 0.306%, and 431.2 kg ha^{-1}, respectively. However, the highest concentration of Phosphorous (P) was found in the sediments eroded from buckwheat field. The enrichment ratio was greater than 1 for all plots except for fallow land covered with grasses. Soil erosion directly contributes to soil nutrient depletion; however, integrated soil fertility management associated with legume-based cropping systems and mulching may reduce its effects on croplands, and these effects can be quantified using rainfall simulation experiments.

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1. Introduction

Soil is a fundamental component of terrestrial ecosystems and supports numerous ecosystem functions that directly influence food production, environmental quality, and ultimately human survival. Human activities exert substantial pressure on soil resources, and the resulting changes in soil condition can, in turn, affect human livelihoods and well-being (Acharya et al., 2019). Despite its critical importance, inappropriate management practices and indiscriminate utilization of land resources have continually impaired the capacity of soils to perform their essential ecological and productive functions. Soil erosion refers to the detachment of soil particles from the parent material and their subsequent transportation by erosive agents, principally water and wind. Although soil erosion and sediment loss have occurred since the beginning of agriculture, their magnitude and intensity have increased considerably as a consequence of expanding agricultural activities and unsustainable land-use practices (Adimassu et al., 2017; Gautam, 1993; Gomez & Gomez, 1984; Karkee, 2004). Soil erosion occurs in several forms, including splash erosion, sheet erosion and rill erosion.

Land degradation resulting from soil erosion is a major global environmental concern because it contributes to the depletion of soil nutrients, deterioration of soil quality, and declining agricultural productivity, thereby posing a substantial constraint to sustainable agricultural development. It has been estimated that approximately 1.7 mm of topsoil is lost annually as a result of soil erosion, whereas the formation of only 1 cm of soil may require nearly 100 years (Adimassu et al., 2017). Runoff generation and sediment loss are generally greater under agricultural land use than under rangeland and forest land, largely because of reduced vegetation cover and greater disturbance of the soil surface (Almas & Jamal, 1999). According to the Global Soil Partnership (GSP, 2017; Maore & Mihara, 2017; Martínez-Mena et al., 2001), approximately 75 billion tons of soil are eroded annually from agricultural areas worldwide, resulting in an estimated economic loss of USD 400 billion each year. Rainfall and overland flow are among the principal drivers of soil erosion and nutrient depletion, resulting in declining soil fertility, reduced agricultural productivity, and broader ecological degradation (Atreya et al., 2008). Consequently, understanding the processes and magnitude of erosion is essential for maintaining soil productivity and ensuring the long-term sustainability of agricultural landscapes.

Nepal is characterized by considerable social, climatic, and geographical diversity, factors that collectively contribute to a range of serious land degradation problems (Chalise et al., 2019). The country is particularly vulnerable to soil degradation because of its steep and fragile terrain, high population pressure, predominantly subsistence-based rural economy, inappropriate and unscientific land-use practices, and increasingly intense rainfall events during the monsoon season. These conditions increase the susceptibility of the landscape to floods, landslides, surface runoff, and soil erosion. The nationwide mean annual soil loss in Nepal has been estimated at approximately 25 t ha^{-1} yr^{-1}, corresponding to a total potential soil loss of about 369 million tons annually (Koirala et al., 2019). Recognizing the severity of this problem, land degradation has become an important policy concern in Nepal. The Agriculture Development Strategy (ADS) has set a target of reducing the area of degraded land from approximately 3.2 million ha to 1.6 million ha by 2035 AD (Ministry of Agricultural Development, 2015). Achieving this objective requires reliable information on erosion processes, vulnerable land-use systems, and appropriate soil and water conservation measures.

Identification of both the magnitude and spatial distribution of areas at risk of soil erosion is essential for the effective planning and implementation of erosion-control practices. Many recent studies have focused on soil erosion modelling through automated procedures, geospatial techniques, and specialized toolboxes for estimating erosion at different spatial scales (Koirala et al., 2019). Although such approaches are valuable for assessing erosion risk over large areas, direct field measurements remain important for understanding erosion processes under specific land-use and management conditions. The most accurate approach for estimating soil erosion resulting directly from rainfall is the measurement of naturally occurring rainfall events. However, natural rainfall measurements have several limitations because rainfall intensity, duration, distribution, and antecedent soil-moisture conditions cannot be controlled. Moreover, extreme rainfall events are difficult to monitor consistently because of their unpredictable and relatively infrequent occurrence. Recent geospatial evidence also indicates that changes in vegetation and land cover can alter erosion susceptibility and can be used to identify areas requiring targeted soil-conservation measures (Sheikh et al., 2016; Watson & Laflen, 1986; Reynolds, 1970; Semebo et al., 2023).

To overcome these limitations, the present study adopted a rainfall simulation approach to investigate soil and nutrient losses under different cropping systems. Rainfall simulation enables rainfall of predetermined intensity and duration to be applied to an experimental erosion plot under controlled conditions. This approach makes it possible to quantify surface runoff, sediment production, and soil loss while reducing the variability associated with naturally occurring rainfall (Humphry et al., 2002; Koch et al., 2024). Furthermore, rainfall simulation provides an opportunity to compare the response of different land-use or cropping systems under similar rainfall conditions, thereby improving understanding of the factors controlling erosion and nutrient transport. Rainfall simulators are widely used in erosion research because they permit controlled and repeatable testing of rainfall-driven surface processes, although simulator design and operating characteristics must be considered when interpreting and comparing results (Humphry et al., 2002; Koch et al., 2024; Wischmeier, 1973; Yadav et al., 2024).

Although soil erosion can be reduced substantially through appropriate management interventions, it is extremely difficult to eliminate it completely. Effective erosion-control strategies therefore aim to minimize soil detachment, reduce runoff velocity, increase water infiltration, and maintain adequate vegetation or residue cover. Commonly adopted measures include mulching, cover cropping, contour farming, strip cropping, conservation agriculture practices, and suitable bioengineering techniques (FAO, 2016). The selection and implementation of such measures should be based on local soil characteristics, topography, land use, cropping practices, and rainfall conditions to ensure their long-term effectiveness. Recent field evidence shows that greater crop-canopy cover can reduce runoff under contrasting rainfall intensities (Jakati et al., 2024). Diversified and intensified cropping systems with greater surface cover have likewise been associated with lower runoff, soil erosion, and nutrient losses than less-diverse or sole-crop systems (Smith et al., 2016; Stefanidis et al., 2021; Yira & Bossa, 2019; Zhang, 2016).

The present study therefore attempts to assess the rate of soil erosion using field-based experimental data. Although a number of studies in Nepal have estimated soil erosion under different land-cover conditions using natural rainfall events, studies employing controlled rainfall simulation remain limited. The findings are expected to provide useful insights into the characteristics of surface runoff, sediment generation, and associated nutrient losses under different cropping systems. Such information may contribute to a better understanding of soil erosion processes and provide a scientific basis for designing and implementing appropriate soil and water conservation measures for sustainable land management. However, field-based evidence that directly compares runoff, sediment loss, and associated nutrient losses among contrasting cropping systems under the same controlled rainfall conditions remains limited in Nepal. Accordingly, the objective of this study was to quantify and compare surface runoff, infiltration, sediment loss, associated nutrient loss, and sediment enrichment ratios across different cropping systems using controlled rainfall simulation at Rampur, Chitwan, Nepal.

2. Materials and Methods

2.1 Study Area

The study was conducted in spring, i.e. on 22 February 2022, in standing field crops at the agronomic farm and horticultural farm of Agriculture and Forestry University (AFU) and at the National Maize Research Programme (NMRP), Rampur, Chitwan, Nepal. The major cropping systems found during the study period were the rice-wheat-based cropping system, maize monocropping, maize intercropping with legumes, continuous vegetable cropping, buckwheat cultivation followed by fallow, maize cropping followed by legumes, rice followed by mustard, vegetables followed by buckwheat, and mustard. Among the different cropping systems, most common systems were identified as in (Table 1). The geographical location of each site under study is represented by the given map (Fig. 1). Similarly, the average maximum temperature during the experiment was approximately 27.9 ºC, and the average minimum temperature was 12.6 ºC. Total rainfall during the experimental period was 51.2 mm.

2.2 Experimental Setup

A stratified random sampling method was used to locate the runoff-plot points where rainfall simulation experiments were carried out. Eight different cropping systems were selected, with each cropping system considered as a factor with eight levels. In each cropping system, three runoff plots were installed for the rainfall simulation. Altogether, runoff plots were installed at 24 points, and 24 composite soil samples were initially collected.

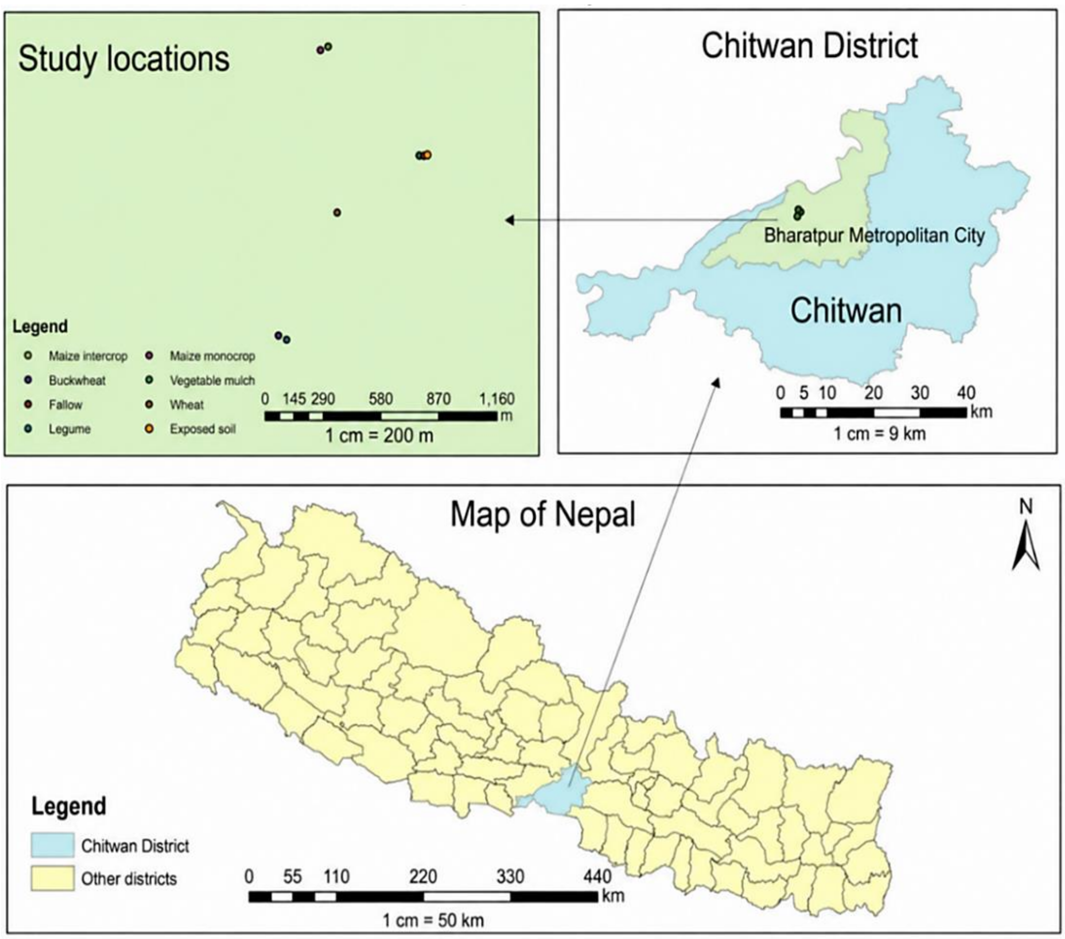

Fig. 1. Map of study area

Table 1. Details of the treatments used in the experiment

Treatments	Cropping system	Symbol
T1	Maize intercropped with legume (*Desmodium* spp.)	MIL
T2	Continuous maize as mono-crop	MM
T3	Vegetable field with organic mulch	VM
T4	Just tilled vegetable field (Exposed soil)	ES
T5	Fallow land covered with grasses	FG
T6	Buckwheat as monoculture followed by fallow	BM
T7	Rice-wheat- based cropping system	RWB
T8	Legume as a sole crop (lentil)	SL

For the selected cropping systems used as treatments, cropping history was recorded.

- **T1:** The selected treatment plot was an experimental plot for push-pull technique for the management of fall armyworm (FAW) in NMRP, Rampur, Chitwan. The experiment had continued for four years with *Desmodium* as an intercrop (Push factor) and Napier grass around the border of the entire research field (Pull factor). Sufficient amounts of organic manure and the recommended dose of fertilisers were used every year.
- **T2:** At NMRP, Rampur, Chitwan, research is regularly conducted on maize. Therefore, this was considered an appropriate location for conducting research on a maize monocropped field.
- **T3:** A horticultural field near the Department of Horticulture, AFU, Rampur, was selected to test the effect of mulching on soil erosion. Broccoli stubble from previous research remained in the field. Vermicompost had been applied to the selected plot. The field was tilled with a spade, and grass residues were used as mulch.
- **T4:** At the same location mentioned above, another plot to which farmyard manure (FYM) had been applied was selected. The plot was tilled with a spade and prepared for the experiment.
- **T5:** Near the Department of Horticulture, there was fallow land covered with grass where lady's finger had been cultivated two years earlier. After harvest, the field was left fallow and was subsequently covered with grasses.
- **T6:** A buckwheat field was selected at the Agronomy Farm of AFU, Rampur, Chitwan, where only buckwheat is cultivated and the field is left fallow for the remaining period. Similarly, sufficient organic manure was also applied to the field.
- **T7:** A wheat field at the Agronomy Farm was selected where wheat was cultivated after rice harvest.
- **T8:** Lentil was cultivated on a farm near the staff quarters of AFU, Rampur, Chitwan, where different crops are grown. Lentil was cultivated after the harvest of summer maize. Poultry manure is used regularly as a source of fertiliser instead of chemical fertilisers.

2.3 Rainfall Simulation and Water Erosion

Rainfall was simulated in early spring 2022 to determine the effects of different cropping systems on nutrient loss and water-quality parameters. Rainfall simulation was conducted for approximately 30 minutes at an intensity of 58 ± 3 mm per hour (Bogunovic et al., 2020). Gravimetric water content prior to rainfall simulation was measured and was found to be low, although it varied slightly among treatments. The mean gravimetric water content of soil at 0-20 cm depth was 12%, while the highest value, 25%, was recorded in the vegetable field and fallow land.

A portable rainfall simulator with a 3 m × 3 m area, made of stainless steel, was used, similar to that described by Humphry et al. (2002). The simulator induced rainfall from 5 m above the ground. The stainless-steel frame could be assembled and disassembled using nuts and bolts. The simulator consisted of a PVC pipe for the water-supply system. Water was forced to the required height using an electric pump (1 hp) fitted in a water tank. The motor had an inline filter to prevent clogging of the shower holes. Simulation was performed during the morning to minimise wind drift because spring days are windy.

A 0.56 × 1.06 m runoff plot was established within each experimental plot using a metal case (Chalise et al., 2019). The metal case was installed in the field so that it enclosed the upper three sides of the plot. A trough made of stainless steel was installed downslope of the runoff plot to collect water. Three rain gauges were set along the sides of the runoff plot to measure rainfall. During each simulation, the time to runoff initiation, total runoff volume, runoff depth, and infiltration were recorded. Runoff samples from the water collector were transferred to large buckets and vigorously shaken to distribute the sediment uniformly, after which two subsamples were collected in 1-litre plastic bottles. The bottles were refrigerated as soon as possible after collection for storage and further analysis. One runoff sample was used to determine concentrations of sediment and sediment-associated C, N, and P, whereas the other sample was used to determine nitrate-N and phosphate-P.

The runoff sample was filtered using Whatman No. 42 filter paper, and the retained material on the filter was oven-dried at 30ºC until a constant weight was obtained (Bremner & Mulvaney, 1982). Oven-dried sediments were scraped, ground to pass through a sieve with 2 mm openings, and subjected to further analysis.

For runoff water, analysis was conducted on solution samples after decantation. Samples were filtered through Whatman No. 42 filter paper if particulates were observed in the supernatant (Kleinman et al., 2007).

2.4 Soil Sampling and Sample Preparation

Selected soil physicochemical properties related to soil erodibility were analysed in the upper 20 cm of soil, while soil texture was determined to a depth of 40 cm. A core ring was used specifically to measure bulk density, and a screw auger was used to collect soil samples from depths of 0-20 and 20-40 cm. Soil-sampling points were located at the four corners of the runoff plots, after which the samples were composited. Three runoff plots were installed in each treatment. Thus, 24 initial soil samples were collected to determine bulk density, total N, available P, exchangeable K, pH, soil texture, and organic matter.

2.5 Soil and Runoff -Water Analysis

Runoff water was stored in a refrigerator for preservation until laboratory analysis. It was then sent to Soil, Water and Air Testing Laboratories Pvt. Ltd. (SWAT), Kathmandu, for analysis of nitrate and phosphate concentrations in the samples. Similarly, sediment and initial soil samples were analysed in the laboratories of Agriculture and Forestry University (AFU), Rampur, Chitwan, Nepal, and Himalayan College of Agricultural Sciences and Technology (HICAST), Purbanchal University (PU), Kathmandu, Nepal, for the following parameters.

2.6 Measurements in the Field

During each simulation, the following parameters were recorded in the field.

2.6.1 Time to Start Runoff

The time to runoff initiation was recorded using a stopwatch.

2.6.2 Runoff Depth

It was calculated using runoff volume and runoff-plot area (Chalise et al., 2019).

$$\text{Runoff depth (mm)} = \frac{\text{Runoff volume(L)}}{\text{Runoff Plot Area}(m^2)}$$

Table 2. Parameters and methods adopted for laboratory analysis

S.N.	Parameter	Methods
1	pH	Potentiometric 1:2 soil-to-water ratio (Jackson, 1973)
2.	Soil Organic Matter (%)	Walkey and Black (Walkley & Black, 1934)
3.	Total N (%)	Kjeldahl Digestion (Bremner & Mulvaney, 1982)
4.	Available P_2O_5 (mg kg^{-1})	Olsen (Olsen et al., 1954)
5.	Available K_2O (mg kg^{-1})	Ammonium acetate extraction method (Jackson, 1967)
6.	Soil texture	Hydrometer (Bouyoucos, 1962)
7.	Bulk density	Core ring (Carter, 1990)
8.	Soil moisture content	Gravimetric method (Jackson, 1967)
9.	Nitrate in runoff sample	4500 NO_3^- F. Cadmium reduction method (APHA, 1992)
10.	Phosphate in runoff sample	4500-P E. Ascorbic Acid Method (APHA, 2017)

2.6.3 Infiltration

The infiltration rate was calculated as the difference between rainfall depth (the amount of rain falling during a given period) and runoff over the simulation period (Chalise et al., 2019).

$$\text{Infiltration(mm)} = \text{rainfall (mm)} - \text{runoff(mm)}$$

2.6.4 Raindrop Size

Raindrop size was calculated using a formula similar to that of Jackson, (1973).

$$d = 0.141d' + 0.888\ mm$$

Where, d = assumed diameter of a spherical drop (mm)

d' = diameter of the drop on filter paper (mm)

Raindrop size was found to be 1.19 mm.

2.6.5 Rainfall Intensity

Rainfall intensity was calculated with the aid of a rain gauge using the following formula and was found to be 58±3 mm per hour.

$$RI = \frac{Rainfall\ depth}{duration\ of\ rainfall}$$

2.6.6 Raindrop Velocity

To determine the velocity of a raindrop of a given diameter falling from a given height, a generalised graph was prepared by Laws in 1941. From the graph, the velocity of a raindrop with a size of 1.19 mm falling from a height of 5 m was found to be 4.6 m s^{-1}.

2.6.7 Raindrop Kinetic Energy

Raindrop kinetic energy was calculated by the formula (Jackson, 1973)

$$KE = \frac{1}{2}\ mass\ of\ raindrop\ (kg) \times square\ of\ velocity\ of\ raindrop\ (m/s)$$

Using this formula, kinetic energy of a raindrop was found to be 9.3 $\times 10^{-6}$ J
(1J= 1kgm^{2}s^{-2})

2.6.8 Enrichment Ratio

The enrichment ratio is expressed as the accumulation of sediments and nutrients at a new deposition site, which can negatively affect soil properties. Eroded materials are generally richer in plant nutrients and fine soil particles than the soil remaining at the eroded site; this relationship is defined by the enrichment ratio. The formula for calculating ER is the same as that used by Jakati et al. (2024).

$$\text{Enrichment ratio} = \frac{\text{Nutrient concentration in sediment}}{\text{Nutrient concentration in parent soil}}$$

2.6.9 Sediment Loss (kg ha^{-1})

Sediment loss during rainfall simulation was calculated using the formula:

$$SL = \frac{\text{Sediment loss (g/l)} \times \text{runoff volume(l)} \times 10}{\text{Plot area}}\ \text{Kg ha}^{-1}$$

2.7 Data Tabulation and Analysis

Data was tabulated using MS Excel and analysed using RStudio with one-way analysis of variance (ANOVA) at the 5% probability level.

3. Results

3.1 Selected Physical and Chemical Properties of Initial Soil Samples

The physical and chemical properties of the soil are shown in Table 3. Soil texture at all experimental sites was sandy loam at both depths. Soil bulk density was highest (1.231 gcm-3) under continuous maize monocropping. Soil moisture content was highest (30.25%) in fallow land covered with grass. Soil pH varied from moderately acidic (5.6) to neutral (7). Soil organic matter content was highest (2.85%) in the vegetable field and lowest (1.54%) under the rice-wheat-based cropping system. Nitrogen content was high in the vegetable field and the field cultivated with sole legume. Similarly, phosphorus content was high in the buckwheat field, followed by the sole-legume field and the field under maize monocropping. Soil potassium content was at a medium level in all cropping systems.

3.2 Influence of Different Cropping Systems on Run Off Start Time, Run Off Volume and Run Off Depth

Runoff start time, runoff volume, and runoff depth differed significantly among the different cropping systems (Table 4).

3.2.1 Runoff Starting Time

Different cropping systems showed highly significant differences in runoff start time. Maize intercropped with legumes took the longest time (23.8 min) to initiate runoff and was statistically similar to fallow land covered with grasses. Similarly, the shortest runoff start time (6.7 min) occurred in the just-tilled vegetable field, followed by the rice-wheat-based cropping system (11.8 min), which was statistically at par with the buckwheat-fallow and maize-monocropping systems.

Table 3. Observed values of selected physical and chemical properties of initial soil samples of different cropping systems at AFU, Rampur, Chitwan, Nepal, 2022

Treatments	Bulk Density (gcm^{-3})	Soil moisture content (%)	pH	Organic matter content (%)	Nitrogen (%)	Phosphorous (kg ha^{-1})	Potassium (kg ha^{-1})
Maize intercropped with legumes (MIL)	1.187	11.88	6.36 Slightly acidic	2.08	0.11 (Medium)	52.48 (Medium	180.6 (Medium)
Continuous maize mono-cropping (MM)	1.231	12.08	6.77 Slightly acidic	2.28	0.14 (Medium)	59.75 (High)	360 (High)
Vegetable field with organic mulch (VM)	0.987	25	5.90 Moderately acidic	2.85	0.19 (High)	54.67 (Medium)	216.2 (Medium)
Exposed/Bare soil (ES)	0.850	28.06	5.67 Moderately acidic	1.84	0.13 (Medium)	52.65 (Medium)	144.6 (Medium)
Fallow land covered with grasses (FG)	1.142	25	6.6 Slightly acidic	1.74	0.09 (medium)	48.28 (Medium)	180.4 (Medium)
Buckwheat mono-cropping followed by fallow (BM)	0.947	12.71	5.88 Moderately acidic	1.91	0.12 (Medium)	109.23 (High)	180.4 (Medium)
Rice-wheat cropping system (RWB)	0.899	13.45	5.90 Moderately acidic	1.54	0.13 (Medium)	48.48 (Medium)	128 (Medium)
Sole legume (SL)	0.855	11.14	7 Neutral	2.21	0.18 (High)	88.24 (High)	345.5 (Medium)

3.2.2 Runoff Volume

Runoff volume was highest (147 Tha-1) in the just-tilled vegetable field and was statistically similar to maize monocropping, the rice-wheat-based cropping system and continuous buckwheat followed by fallow cropping system. In contrast, fallow land covered with grasses produced the lowest runoff volume (37 Tlha-1), which was statistically at par with maize intercropped with legumes. Mulching reduced runoff volume by 33.1% compared with bare soil. Similarly, maize intercropping with legumes reduced runoff volume by 71.2% compared with maize monocropping.

3.2.3 Runoff Depth

Rainfall depth was similar across all cropping systems, averaging 30 mm during the simulation period, whereas runoff depth was highly affected by the different cropping systems (Table 4). Runoff depth was highest (24.77 mm) in bare land and lowest (6.23 mm) in fallow land covered with grasses, followed by intercropping.

3.3 Effect of Different Cropping Systems on Infiltration and Sediment Loss

Infiltration and sediment loss differed significantly among the treatments (Table 5). Infiltration was highest in fallow land covered with grasses and lowest in bare soil. The highest sediment loss was recorded in bare soil compared with soil covered with plants.

Table 4. Effect of different treatments on runoff start time, runoff volume and runoff depth at Rampur, Chitwan, Nepal, 2022

Treatments	Runoff starting time (min)	Runoff volume ($Tlha^{-1}$)	Runoff depth (mm)
Maize intercropped with legumes (MIL)	23.8a	38.7c	6.51c
Continuous maize mono-cropping (MM)	11.77de	134.3ab	22.63ab
Vegetable field with organic mulch (VM)	18.60abc	98.3b	16.57b
Exposed/Bare soil (ES)	6.73e	147a	24.77a
Fallow land covered with grasses (FG)	23.33a	37c	6.23c
Buckwheat mono-cropping followed by fallow (BM)	15.17bcd	117ab	19.71ab
Rice-wheat cropping system (RWB)	11.80cde	132.7ab	22.35ab
Sole legume (SL)	19.33ab	114bc	20.68b
Grand Mean	16.32	102.4	17.43
SEM (±)	1.390	8.87	1.493
LSD (0.05)	4.167	26.59	4.476
P Value	<0.001	<0.001	<0.001
Level of significance	***	***	***
CV%	14.75	15.0	15

****: highly significant at P<0.001, *: significant at p<0.01, means in column followed by same letter(s) are not significantly different*

Table 5. Effect of different cropping systems on infiltration and sediment loss at Rampur, Chitwan, Nepal, 2022

Treatments	Infiltration (mm)	Sediment loss (kg $ha^{-1)}$
Maize intercropped with legumes (MIL)	20.53a	104.2cde
Continuous maize mono-cropping (MM)	7.82bc	459.3b
Vegetable field with organic mulch (VM)	13.19b	57.7d
Exposed/Bare soil (ES)	5.20c	842.3a
Fallow land covered with grasses (FG)	23.67a	12.3e
Buckwheat mono-cropping followed by fallow (BM)	10.80bc	161.9cd
Rice-wheat cropping system (RWB)	7.79bc	220.3c
Sole legume (SL)	10.51bc	108.8cd
Grand Mean	12.44	245.85
SEM (±)	1.452	36.282
LSD (0.05)	4.352	108.773
P Value	<0.001	<0.001
Level of significance	***	***
CV%	20.21	26.9

****: highly significant at P<0.001, means in column followed by same letter(s) are not significantly different*

3.3.1 Infiltration

Infiltration was highest (23.67 mm) in fallow land covered with grass and was statistically similar to maize intercropped with legumes. Similarly, the just-tilled vegetable field (ES) showed the lowest infiltration (5.20 mm), which was statistically at par with the rice-wheat-based cropping system, the maize-monocropping system, buckwheat monocropping system and sole legume monocropping system.

3.3.2 Sediment Loss

Total sediment loss was highest (842.3 kg ha-1) in the just-tilled vegetable field and lowest in fallow land covered with grasses (12.3 kg ha-1), as shown in Table 5. The order was: bare land > maize monocropping > rice-wheat > buckwheat > legumes > intercropping > mulching > fallow land covered with grasses.

Sediment yield per plot in fallow land covered with grasses was very low. However, sediment-associated N, P, and K in fallow land covered with grasses were below the detection limit (BDL).

3.4 Nutrient Loss

Losses of soil nutrients, such as total nitrogen (N), available phosphorus (P), and available potassium (K), associated with sediment differed significantly among treatments, whereas there was no significant difference in organic matter (OM) loss. Losses of nutrients such as N, and K were highest (0.307% and 431.2 kg ha^{-1}) in bare land and lowest (0.243%, and 220.8 kg ha^{-1}) in intercropping. Similarly, loss of P was the highest (159.34a) in buckwheat field and the lowest (84.32) under maize intercropping system (Table 6).

Nitrate loss via runoff water differed significantly among cropping systems (Table 7). The highest loss (23.67 mg l^{-1}) of Nitrate was found under sole-legume (lentil) cropping, while the lowest value (6.93 mg l^{-1}) was observed in fallow land covered with grasses. Similarly, Phosphate was significantly highest (0.820 mg l^{-1}) in the bare plot and buckwheat-cultivated field, which were statistically at par with maize monocropping and sole-lentil cultivation. The lowest value (0.0637 mg l^{-1}) was observed in fallow land covered with grasses, which was statistically at par with maize intercropping, mulching, and the rice-wheat-based cropping system.

Table 6. Effect of different cropping systems on soil nutrient loss at Rampur, Chitwan, Nepal, 2022

Treatments	OM of sediment (%)	Sediment N (%)	Sediment P_2O_5 (kg ha^{-1})	Sediment K_2O (kg ha^{-1})
Maize intercropped with legumes (MIL)	5.273	0.243b	84.32d	220.80d
Continuous maize mono-cropping (MM)	5.404	0.293ab	115.38bc	363.97ab
Vegetable field with organic mulch (VM)	5.277	0.260ab	85.37cd	250.13cd
Exposed/Bare soil (ES)	5.65	0.307a	133.07ab	431.20a
Fallow land covered with grasses	BDL	BDL	BDL	BDL
Buckwheat mono-cropping followed by fallow (BM)	5.367	0.260ab	159.34a	256.71cd
Rice-wheat cropping system (RWB)	4.27	0.270ab	130.44ab	304.87bc
Sole legume (SL)	5.310	0.243b	106.25bcd	243.53cd
Grand Mean	5.22	0.268	116.31	295.89
SEM (±)	0.356	0.011	6.303	15.759
LSD (0.05)	1.08	0.034	19.119	47.8
P Value	0.110	0.0085	<0.001	<0.001
Level of significance	ns	**	***	***
CV%	11.6	7.23	9.39	9.2

****: highly significant at P<0.001, **: significant at p<0.01, means in column followed by same letter(s) are not significantly different: ns= non-significant and that ANOVA used seven groups*

Table 7. Effect of different cropping systems on soil nutrient loss via runoff at Rampur, Chitwan, Nepal, 2022

Treatments	Nitrate (mg l^{-1})	Phosphate (mg l^{-1})
Maize intercropped with legumes (MIL)	12.97ab	0.078b
Continuous maize mono-cropping (MM)	19.23ab	0.6753a
Vegetable field with organic mulch (VM)	14.53ab	0.0783b
Exposed/Bare soil (ES)	21.88a	0.820a
Fallow land covered with grasses (FG)	6.93b	0.0637b
Buckwheat mono-cropping followed by fallow (BM)	18.82ab	0.820a
Rice-wheat cropping system (RWB)	19.60ab	0.3177b
Sole legume (SL)	23.67a	0.722a
Grand Mean	17.20	0.44
SEM (±)	2.637	0.107
LSD (0.05)	7.91	0.322
P Value	0.0079	<0.001
Level of significance	**	***
CV%	26.5	42.4

****: highly significant at P<0.001, **: significant at p<0.01, means in column followed by same letter(s) are not significantly different*

3.5 Nutrient Enrichment Ratio

Among the different cropping systems, the nutrient enrichment ratio was highest in bare land for most nutrients (OM, N, and K, with values of 2.937, 2.388, and 2.117, respectively) and lowest under mulching (1.518, 1.362, and 1.128, respectively). Similarly, the nutrient enrichment ratio was highest for OM (2.54), followed by N (1.94), P (1.75), and K (1.49).

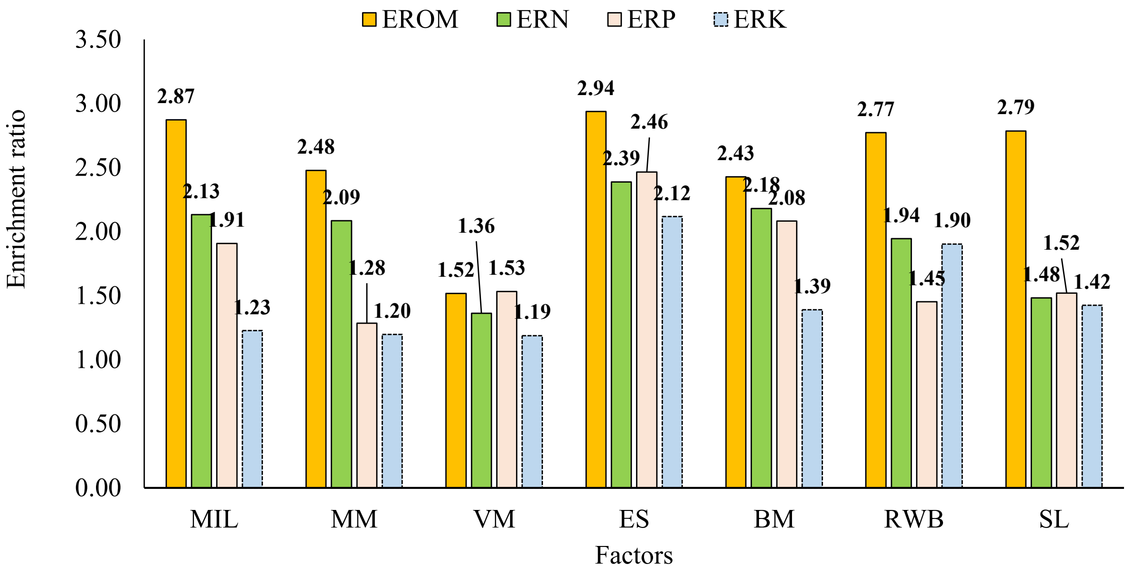

Fig. 2. Enrichment ratio of sediments under different cropping systems

4. Discussion

4.1 Runoff and Infiltration

The longest runoff start time was observed in maize intercropped with legumes and in fallow land covered with grasses, followed by mulching, whereas the shortest time occurred in the bare field. A longer runoff start time indicates better infiltration, and vice versa. Mulching reduced runoff volume by 33.1% compared with bare soil. Similarly, maize intercropping with legumes reduced runoff volume by 71.2 % compared with maize monocropping.

The result was supported by the findings of Nyawade et al. (2019), who compared monocropping, intercropping, and bare land in relation to soil erosion. This might be due to better soil cover by plant roots, which maintains soil structure, thereby increasing infiltration capacity and delaying runoff generation. The plant canopy might also have reduced soil-surface sealing caused by raindrop impact, thereby maintaining higher infiltration rates and lower runoff (Koch et al., 2024).

For the highest infiltration recorded in fallow land covered with grasses, soil structure was reported to improve when cultivated land was converted to grass, leading to improvements in soil aggregate distribution and stability, air permeability, and hydraulic conductivity over time (Lindstrom et al., 1998). This might be due to saturated hydraulic conductivity, extensive root density, and surface roughness, which are generally greater in natural fallow than in cropland and thereby increase infiltration in natural fallow (Koirala et al., 2019; Yira & Bossa, 2019).

Similarly, under mulching, organic mulch increases surface roughness and rainfall interception, thereby delaying runoff generation; the resulting delay in runoff flow enhances infiltration during rainfall. A reduction in soil runoff of up to 18% was reported with rice-straw mulching in Kathmandu (Atreya et al., 2008). This may be attributed to surface cover, which reduced soil loss under the different treatments. The effectiveness of surface cover can be influenced by rainfall amount and intensity; however, increased surface cover effectively reduced soil loss.

This trend indicates that adequate surface cover and plant roots are necessary to protect soil and reduce nutrient loss.

4.2 Sediment Loss

Negligible sediment loss was observed from fallow land covered with grasses, whereas the lowest sediment loss among the cultivated treatments was recorded under mulching, followed by intercropping. This may be attributed to the protective effect of crop-residue mulch applied at the soil–air interface. Mulch protects the soil surface from direct raindrop impact, decreases runoff velocity and shear force, reduces both the amount and rate of surface runoff, and acts as an effective sediment trap (Kumari et al., 2024). Similar findings were reported by Li et al. (2024), who observed that soil erodibility under contour tillage combined with straw mulching was lower than that under contour tillage without mulching. Mulch also provides a cushioning effect against the impact of raindrops on soil aggregates and forms a mechanical barrier to surface runoff. Consequently, it enhances water infiltration into the soil profile, traps transported sediment, and helps prevent surface sealing (Watson & Laflen, 1986). Furthermore, crop-residue mulches can enhance soil microbial activity and increase soil organic matter content, thereby improving soil aggregate stability over the long term (Lindstrom et al., 1998). Among the various soil-conservation practices that have been implemented, mulching has been successfully applied in agricultural lands because of its effectiveness in reducing runoff and sediment loss (Robichaud et al., 2013; Zhang, 2016).

The results obtained in the present study are in good agreement with the findings of Koch et al. (2024), who demonstrated that maintaining adequate surface cover can contribute significantly to the conservation of soil and water resources. In the intercropping treatment, the reduction in soil loss may be attributed to the greater surface cover and the dense barrier provided by *Desmodium*.spp. This vegetative cover reduced runoff velocity and increased the time available for suspended soil particles to settle. In addition, the dense growth of *Desmodium* spp. provided an effective filtration barrier, allowing sediment to be retained before runoff left the plot. These combined effects ultimately resulted in a lower amount of sediment loss under the intercropping system.

The relatively low infiltration observed in the cultivated field may have resulted from the disruption of soil structure caused by repeated cultivation and soil compaction associated with the use of farm implements (Bharati et al., 2002; Maqubela et al., 2009). Such disturbances can reduce soil porosity and restrict the continuity of pore spaces, thereby limiting the movement of water into the soil profile. Consequently, reduced infiltration may increase the proportion of rainfall converted into surface runoff, thereby increasing the potential for soil and nutrient losses from cultivated land.

4.3 Nutrient Loss

Nutrient loss was highest from bare land, where the greatest sediment loss was also recorded. This may be explained by the fact that a substantial proportion of soil fertility is concentrated in the surface soil layer. Because essential plant nutrients are generally present at relatively high concentrations near the soil surface, they can be readily detached and transported through surface runoff and eroded sediment. Bare plots, owing to the absence of protective land cover and the deterioration of soil physical structure, were therefore more susceptible to nutrient depletion than plots under cultivated crops (McHugh et al., 2007). Inadequate land cover increases soil erosion by exposing the soil surface directly to the physical and mechanical impact of raindrops, which promotes aggregate breakdown. This process may subsequently result in soil-surface sealing, reduced infiltration, increased surface runoff, and ultimately greater soil and nutrient losses (Issaka & Ashraf, 2017).

Nutrient losses through runoff, particularly in the form of nitrate and phosphate, were highest under sole legume cropping system and lowest from fallow land covered with grasses. Phosphate loss was also comparatively high from the buckwheat field. This pattern may have been influenced by the initial nutrient status of the soil, together with the quantity of sediment removed from each treatment. The relatively high phosphate loss observed from the buckwheat and legume fields may also be associated with root-derived substances that enhance the solubilization of phosphorus that would otherwise remain poorly available to plants (Valenzuela & Smith, 2002). Such mobilization may increase the amount of phosphorus present in more readily transportable forms within the surface soil (Sai et al., 2021).

In addition, buckwheat roots have been reported to possess a relatively high capacity for the accumulation of inorganic phosphorus. Consequently, when buckwheat biomass is incorporated into the soil, its rapid decomposition can release phosphorus and increase its availability to subsequent crops (Mishra & Rai, 2013). Although this process may improve nutrient availability within the cropping system, it may also increase the potential for phosphorus loss where substantial runoff and sediment transport occur. The observed nutrient-loss pattern therefore appears to reflect the combined influence of surface cover, soil erosion intensity, initial soil nutrient status, and crop-specific nutrient mobilization processes.

4.4 Enrichment Ratio

Nutrients assessed in all cropping systems had ER values greater than 1, demonstrating the ability of soil erosion to transport the most fertile soil layers out of cropped areas (Bashagaluke et al., 2018; Pandey et al., 2016). The high ER of nutrients in sediments might be due to the selective transport of fine particles that are rich in plant nutrients (Jakati et al., 2024). Generally, soil sediments contain higher amounts of soil nutrients in available forms than the soil from which they are eroded (Sai et al., 2021).

5. Conclusions

The findings demonstrate that cropping systems influenced runoff, infiltration, sediment loss, and associated nutrient losses under simulated rainfall conditions at Rampur, Chitwan. Exposed soil was particularly susceptible to erosion, whereas fallow land covered with grass showed the lowest sediment loss and comparatively favorable infiltration. Mulching reduced runoff volume by 33.1% compared with bare soil, while maize intercropping with legumes reduced runoff volume by 71.2% compared with maize monocropping. Sediment-associated nutrient losses were also greatest from exposed soil and comparatively lower where protective vegetation or mulch was present. Enrichment ratios greater than 1 indicated that eroded sediment contained proportionally greater concentrations of nutrients than the source soil. These results emphasize the importance of maintaining soil-surface cover and root systems for reducing the detachment and transport of soil and nutrients. Under the conditions evaluated in this study, legume-based intercropping and mulching were associated with improved protection against runoff and erosion. Rainfall simulation was useful for comparing erosion responses among contrasting cropping systems under controlled rainfall conditions.

6. Limitations

The study was conducted at a single location and during one experimental period using relatively small runoff plots under simulated rainfall. Consequently, the observed runoff, infiltration, sediment loss, and nutrient-loss responses represent the specific soil, cropping, and rainfall-simulation conditions evaluated at Rampur, Chitwan. Natural rainfall varies in intensity, duration, drop characteristics, antecedent moisture conditions, and seasonal distribution. Therefore, broader evaluation across multiple locations, seasons, rainfall regimes, and larger runoff plots would strengthen the applicability of the findings to other agricultural environments.

7. Recommendations for Further Research

Several recommendations arising from this study may be useful for further research on quantifying soil erosion and nutrient loss. Because soil quality is declining, largely due to soil erosion, quantification of soil and nutrient loss may help in developing suitable conservation methods.

- Similar studies are recommended in multi-location trial environments to enable generalisation of the findings.
- Runoff plots with wider dimensions could be used to minimise errors.
- Similar research could be conducted involving different conservation practices, such as minimum tillage, different types of mulching, and strip cropping, while extending nutrient-loss evaluation to calcium and magnesium, which are highly subject to selective chemical erosion that contributes to soil acidification.
- The accuracy of soil-erosion and nutrient-loss quantification could be improved by conducting studies over longer durations, such as 3-4 growing periods.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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