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# INTERCEPTING SEDIMENT AND NUTRIENT LOSS: THE ROLE OF SOIL AMENDMENTS UNDER DIFFERENT SLOPE GRADIENTS

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**Abstract**

*Agricultural land use on sloppy areas is susceptible to nutrient loss via surface runoff, which would result in negative impacts on downstream waters. However, the linkage between nutrition loss and off-site crop production has been rarely reported in the sloppy lands of Pakistan. Therefore, this study aimed to evaluate the impact of soil amendments on runoff, sediment, and nutrient loss across different soil slope gradients. A four-year field study was conducted at the Soil and Water Conservation Research Station, Fateh Jang, from 2019 to 2022 to evaluate the benefits of various soil amendments to minimize the sediment and nutrient loss. Three soil amendments, including chemical fertilizer (29:79:29 NPK kg ha-1), compost (750 kg ha-1), and gypsum (1000 kg ha-1), were applied at various slope gradients (1%, 5%, and 10%) alongside a control (no amendment) while using groundnut as test crop. After every rainfall event of ≥ 20 mm, run-off was collected in collection drums (200 L capacity) installed against every slope gradient. Following the collection, the quantity of water, sediment, and nutrients lost was measured for comparison. Results showed that a significant decrease in water (39% and 32%), sediment (45% and 32% respectively), and nutrient loss (71% and 106%) was quantified in gypsum and compost treatments, respectively, compared to the control. It was further noticed that chemical fertilizer treatment resulted in higher pod (1297 kg h-1) and straw yields (1462 kg h-1), but could not offer an effective shield against sediment and nutrient loss. We found that the higher the slope gradient, the higher the soil, water, and nutrient losses. Hence, it is concluded that gypsum and compost should be applied along with chemical fertilizer to reduce the runoff, sediment and nutrient loss without compromising the grain and straw yield of groundnut. Therefore, the prioritization of gypsum and compost treatments along with fertilizers is recommended as an effective strategy for mitigating soil and water erosion and ensuring sustainable agricultural practices in regions characterized by undulating topography.*

**Keywords:** *Nutrient loss, Runoff, Soil amendments, Slope gradient*

## INTRODUCTION

The livelihoods of two-thirds of Pakistan's rapidly expanding population heavily rely on dry-lands, primarily through agro-pastoral activities. However, agriculture in rainfed areas faces significant challenges, including moisture stress, soil and water erosion, nutrient deficiency and soil crusting (1). Soil erosion exacerbates these challenges by diminishing agricultural productivity due to physico-chemical degradation, leading to a decline in soil fertility (2). The loss of soil nutrients through runoff and sediment transport is a prominent factor contributing to decreased soil fertility (3, 4). The convergence of drought, water scarcity, and soil and water loss poses significant challenges for socially and economically sustainable development in arid and semi-arid regions of Pakistan. Extreme losses of natural and financial resources due to soil erosion have a detrimental effect on the economies of affected areas, leading to agro-ecological, environmental, and watershed-function issues (5). Water and soil are essential elements for crop growth, and conserving rainfall water is crucial for sustainable agriculture in rainfed areas like the Pothohar region, a rainfed upland area characterized by undulating topography, moderate to steep slopes, and erratic rainfall patterns, which is vulnerable to soil, nutrient, and moisture loss. Topographic features, such as slope gradient and length, influence soil erosion and nutrient loss. Steeply sloped farms are more prone to soil erosion (6) while the impact of slope gradient on nutrient loss is complex and can have both positive and negative effects (7-9).

Scientists have proposed various strategies to mitigate soil erosion and run-off. In this connection application of soil amendments is one the easy and cost-effective approach. Since gypsum reduces erosion by stabilizing the soil and by preventing runoff during heavy rain storms. It improves infiltration by reducing the soil compaction (4). Studies have demonstrated that gypsum application can decrease soil pH, increase nutrient availability, and minimize soil crusting, erosion, and runoff (10, 11). Additionally, gypsum can improve plant nutrient uptake, especially macronutrients (12). Similarly, addition of compost also improves soil structure and fertility by adding organic matter in the soil. Compost boosts the ability of the soil to retain moisture which results in soil loss by reducing water runoff (13). Research has shown that soil amendments, such as organic manures and gypsum, can enhance soil's water retention capacity, reduce erosion, and improve nutrient availability (14). However, most of the studies have mainly focused on sediment losses and water runoff, their responses to soil conservation measures, and less consideration has been given to nutrient losses induced by soil erosion (15). Nutrient loss at different slope gradients, a clear relationship was observed between slope gradient and the amount of nutrient loss. Soil erosion reduces the agricultural value of lands via physico-chemical degradations. Soil nutrient loss through runoff and sediment, is a major driver for soil fertility decline in sloppy lands. The eroded sediments or soil are highly concentrated with crop nutrients, which are washed away from farmlands. Erosion based constraints coupled with unfavorable climatic conditions define the productivity of farming systems. Soil erosion leads to extreme losses of economic and environmental resources which negatively impact the economies of affected region (16). To address this statement study was planned to intercept the losses caused by runoff on sloping lands with cost effective and easy to use and farmer friendly soil amendments like compost and gypsum. This study aims to investigate the effects of slope gradient and soil amendments on runoff, sediment, and nutrient loss from gently sloping agricultural fields, with a focus on groundnut crop yield.

# MATERIALS AND METHODS

## EXPERIMENTAL SITE AND TREATMENTS

The study was conducted at Soil and Water Conservation Research Station, Fateh Jang (latitude 33.55° N, longitude 72.58° E and 402 m high from the sea level), from 2019-2022 to evaluate the role of soil amendments on runoff, sediment and nutrients loss at different slope gradients (1%, 5% and 10%). Prominent crop of rainfed areas, groundnut was cultivated to test the hypothesis. Three different types of soil amendments i.e., chemical fertilizer @ 29:79:29 NPK kg ha$^{-1}$, compost @ 750 kg ha$^{-1}$ and gypsum @ 1000 kg ha$^{-1}$ were applied. Keeping in view the undulating topographic features of the lands of this particular tract, four plots were selected for each treatment plan. Twelve runoff plots were mounted on the experiment site each plot was 5 m long and 2 m wide which contains an area of 10 m$^2$. To collect rainwater runoff, sediment and nutrients loss 200 L capacity plastic drums were connected to each slope gradient with a 5-inch diameter plastic pipe down the slope. During the study period, no runoff overflow occurred from the collection tanks. Additionally, the tanks were fully covered to minimize evaporation losses. All slope restrictions were constructed with cement and was raised up to 15 cm to avoid intermixing of sediment during rainfall time. Soil crusting effect was reduced with manually ploughing at end of each cropping season. All slopes were maintained to compensate lost soil when desired. Kharif crop groundnut was grown on slopes plot in respective growing seasons. One plot was kept fallow as a check plot in all slope gradients.

## OBSERVATIONS RECORDED

Rainwater runoff, sediment and nutrients loss were monitored during the cropping season each time after heavy rainfall erosion data was collected. Over the entire years, runoff was measured. The amount of water that was recorded was converted to cubic meters per hectare ($m^3$ $ha^{-1}$). Similar relationships were found between the amount of washed-out soil and the tons per hectare (t $ha^{-1}$) measurement unit. All rainfall events with a volume of 20 mm or more were linked to runoff data. Following every 20 mm or more of rain, 1 L of runoff water was sampled from each container after stirring and mixing in order to calculate the runoff volume and determine how much soil and water were lost per rainfall event. The depth of runoff in each container was calculated for measuring volume of runoff. To calculate the sediment concentration and soil nutrient loss, the leftover sediment was dried at low temperature at (45C° for 12 h) after drying samples were shifted to laboratory for analyses. Then, using this data (17) description of cumulative soil, water, and nutrient loss per cropping period was noted annually for each plot across all slope gradients. The nutrient concentrations in the runoff were measured for three primary nutrients: nitrogen (N), phosphorus (P), and potassium (K). Samples were collected from slopes from different slope gradients: normal slope (1%), moderate (5%) and steep (10 %). Soil nutrients losses was measured after collecting soil data in each rainy season then taking a cumulative soil sample for analysis of NPK in each year. Methods used for the analysis of Nitrogen were Kjeldahl apparatus, Olsen P for Phosphorous and flame photometry for estimation of potassium.

## STATISTICAL ANALYSIS

The data was statistical analyzed using the analysis of variance (ANOVA) method for evaluation of differences in treatments. Statistical design was randomized complete block design (RCBD) and data was analyzed by using statistics 8.10. Treatments means were compared using the Least Significant Difference (LSD) test at a 5% probability level.

**Table I.** Soil properties at the study site

| Soil properties | Value | Unit |
|---|---|---|
| pH | 8.02 | - |
| Bulk density | 1.61 | g $cm^{-3}$ |
| Organic carbon | 0.78 | % |
| Electrical conductivity ($EC_e$) | 1.23 | dS $m^{-1}$ |
| Available phosphorus | 4.52 | mg $kg^{-1}$ |
| Extractable potassium | 74 | mg $kg^{-1}$ |
| Texture | Silt Loam | - |

## RAINFALL

Maximum rainfall was occurred during the months of July to September, there were six erosive rainfall events was recorded in each year during the crop season (Fig. 1). For the period 2019–2022, the annual average rainfall amounts ranged from 99 mm in 2019, 140 mm in 2020, 129 mm in 2021 and 106 mm in 2022.

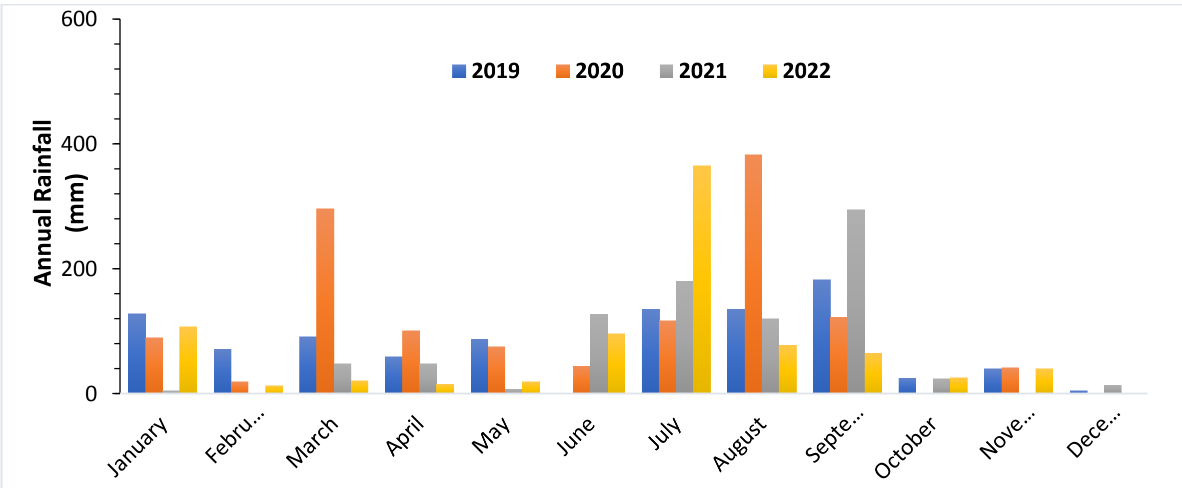


**Fig. 1.** Annual average monthly rainfall at study site recorded at meteorological observatory station at soil and water conservation research station Fateh Jang

# RESULTS & DISCUSSION

## RAINWATER RUNOFF (m-3 ha-1)

Water runoff was recorded after every rainfall ≥20 mm and a considerable correlation was found among different soil amendments and slope gradients (Fig. 2). Water runoff was highly inconsistent among and within different slopes. In 2019 highest water runoff (600 $m^{-3}$ $ha^{-1}$) was recorded at 10% slope gradient in control followed by the chemical fertilizer and compost whereas minimum (470 $m^{-3}$ $ha^{-1}$) was recorded at 1% slope gradient in gypsum treated plots. The data recorded in 2020 represent that maximum water runoff was recorded (376 $m^{-3}$ $ha^{-1}$) in control plots at 10% slope gradient followed by the chemical fertilizer and compost whereas minimum (124 $m^{-3}$ $ha^{-1}$) was recorded at 1% slope gradient in gypsum. The similar trend was eminent in the following years. It was noticed that for the 5% slope gradient gypsum performed best as compared to compost followed by chemical fertilizer and control. Overall gypsum performed best followed by compost and chemical fertilizer. Maximum water runoff was recorder at 10% slope gradient followed by 5% and minimum was recorded at 1% slope gradient. The results show significant variability in water runoff which may be due to rainfall variation, slope gradient and soil amendment. The study was supported with the same finding (18). In general, the mechanism involved in water runoff is through sheet erosion on the slopes as water flows over the soil surface and carries away a thin layer of soil. Other findings reported that the other way to more soil erosion generation is the slope gradients which directly affect the runoff volume. The slope gradient is considered as the main factor for water runoff and soil erosion (19). As for as soil amendments are concerned gypsum performed the best on all slope gradients. Gypsum breaks up the compacted soil and improves infiltration rate of soil which results in less water runoff.

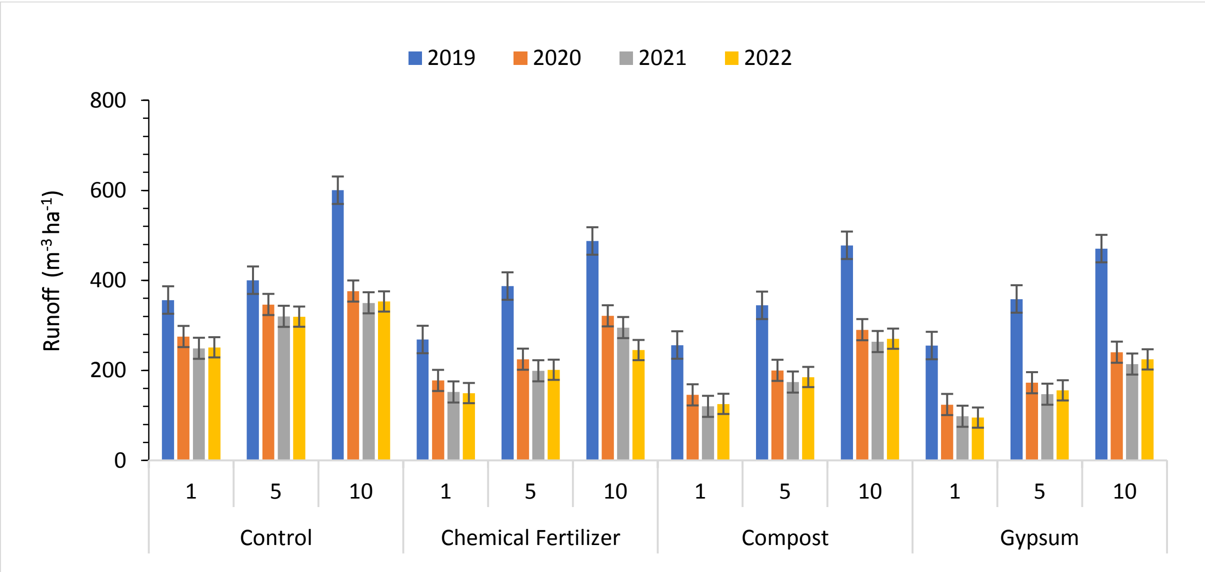


**Fig. 2.** Impact of soil amendments on rainwater runoff ($m^{-3}$ $ha^{-1}$) under different slope gradients. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

## SEDIMENT LOSS (t ha-1)

Soil sediment loss was recorded after every rainfall ≥20 mm and a considerable correlation was found among different soil amendments and slope gradients (Fig. 3). Sediment loss was highly inconsistent among and within different slopes. In 2019 highest sediment loss (3.42t $ha^{-1}$) was recorded at 10% slope gradient in control followed by the chemical fertilizer whereas minimum sediment loss (0.96 t $ha^{-1}$) was recorded at 1% slope gradient in gypsum treated plots. The data recorded in 2020 represent that maximum was recorded (3.12t $ha^{-1}$) in control plots at 10% slope gradient followed by the chemical fertilizer whereas minimum (0.81t $ha^{-1}$) was recorded at 1% slope gradient in gypsum. The similar trend was eminent in the following years. It was noticed that for the 5% slope gradient gypsum performed best as compared to compost followed by chemical fertilizer and control. Overall gypsum performed best followed by compost and chemical fertilizer. Maximum sediment loss was recorder at 10% slope gradient followed by 5% and minimum was recorded at 1% slope gradient as the slope gradient is main factor for controlling soil erosion

(19). The results show significant variability which may be due to rainfall variation, slope gradient and soil amendment. The study was supported with the same findings by (18). Soil sediment loss and concentration generally related with the amount of rainfall (20). Heavy rainfall with short duration and high intensity causes more soil sediment loss (21). Loss of soil sediments was more at rainfall with intensity up to or above 20 mm (19). Soil detachment increased with high intensity rainfall events and leads towards increased surface runoff and erosion rates on fallow and feebly vegetative fields (22, 23).

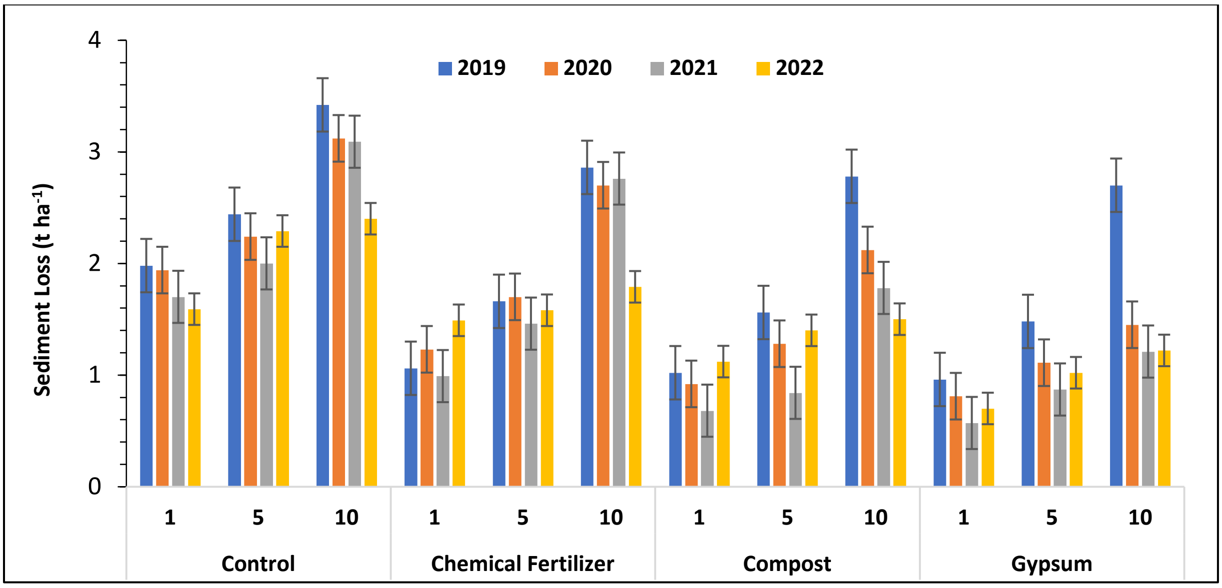


**Fig. 3.** Impact of soil amendments on sediment loss (t ha$^{-1}$) under different slope gradients. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

## POD YIELD

Crop growth and yield trend was similar regarding slope gradients during all study years except soil amendments in which changing trend was observed in all soil amendments. The data of pod yield varied significantly in all soil amendments. A significant change was recorded among all slope gradients. It was absorbed that with increase in soil gradient the pod yield was decreased in all study years. Maximum yield was recorded at 1% slope gradient followed by 5% and 10%. The average pod yield of chemical fertilizer, compost and gypsum was 1410 kg ha$^{-1}$, 1192 kg ha$^{-1}$ and 1302 kg ha$^{-1}$ respectively on 1% slope gradient. The average pod yield of chemical fertilizer, compost and gypsum was decreased to 1275 kg ha$^{-1}$, 1109 kg ha$^{-1}$ and 1172 kg ha$^{-1}$ on 5% slope gradient. Similarly, the pod yield of chemical fertilizer, compost and gypsum was decrease to 1206 kg ha$^{-1}$, 1020 kg ha$^{-1}$ and 1095 kg ha$^{-1}$ respectively at 10% slope gradient. The pod yield decreased with an increase in topographic gradient showing antagonistic effect of slope gradient on yield (Fig. 4), another study reported the similar findings (24). In a study it was reported that gypsum increases the pod yield by conserving moisture (4, 25).

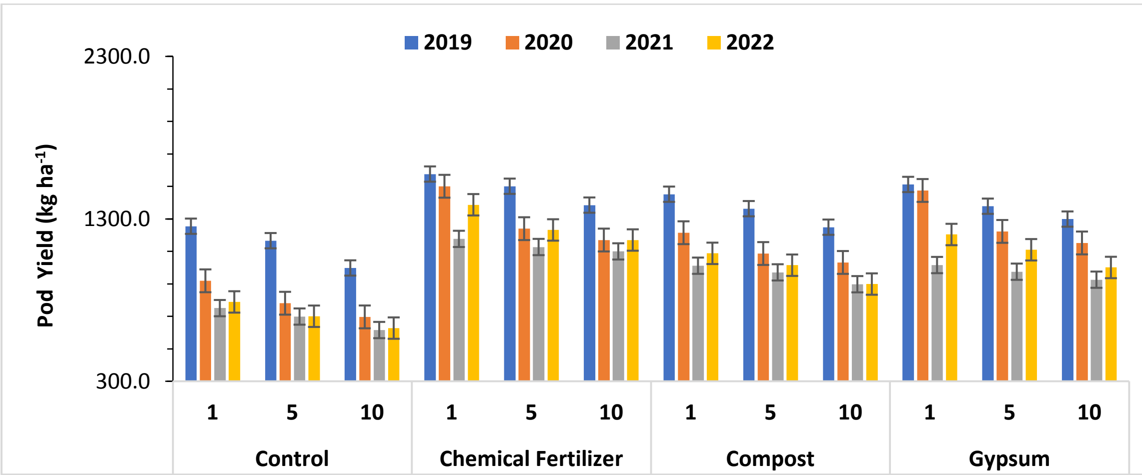


**Fig. 4.** Impact of soil amendments on pod yield (kg ha$^{-1}$) under different slope gradients. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

## BIOMASS YIELD

Crop biomass yield trend was similar regarding slope gradients during all study years except soil amendments in which changing trend were observed in all soil amendments. The data of biomass yield varied significantly in all soil amendments. A significant change was recorded among all slope gradients. It was absorbed that with increase in soil gradient the biomass yield was decreased in all study years. Maximum yield was recorded at 1% slope gradient followed by 5% and 10%. The average biomass yield of chemical fertilizer, compost and gypsum was 1588 kg $ha^{-1}$, 1457 kg $ha^{-1}$ and 1515 kg $ha^{-1}$ respectively on 1% slope gradient. The average biomass yield of chemical fertilizer, compost and gypsum was decreased to 1450 kg $ha^{-1}$, 1378 kg $ha^{-1}$ and 1406 kg $ha^{-1}$ on 5% slope gradient. Similarly, the biomass yield of chemical fertilizer, compost and gypsum was decrease to 1350 kg $ha^{-1}$, 1261 kg $ha^{-1}$ and 1228 kg $ha^{-1}$ respectively at 10% slope gradient. The biomass yield decreased with an increase in topographic gradient showing antagonistic effect of slope gradient on straw yield (Fig. 5).

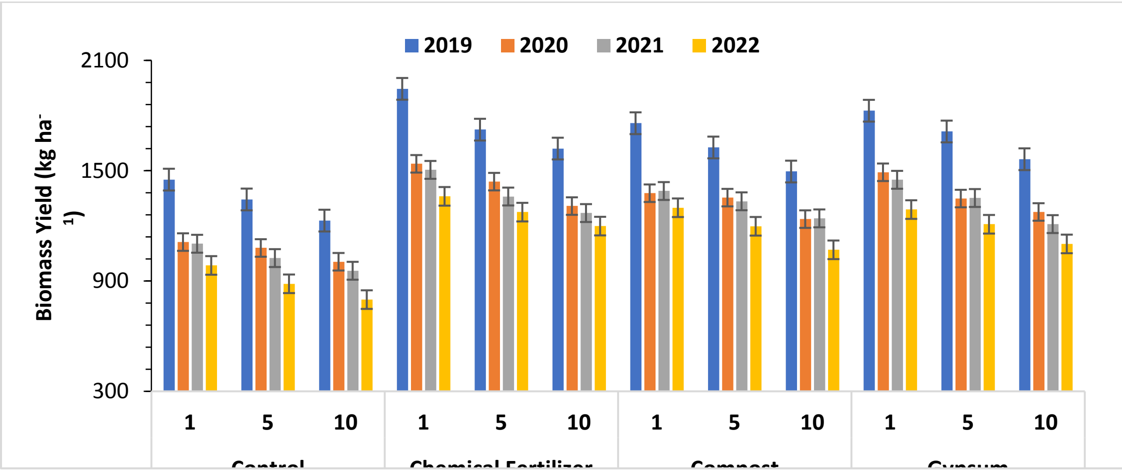


**Fig. 5.** Impact of soil amendments on straw yield (kg $ha^{-1}$) under different slope gradients. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

## SOIL NUTRIENTS LOSSES UNDER DIFFERENT SLOPE GRADIENTS

Nutrient loss was affected by slope gradient, soil amendments as well as by the interaction of both. In case of slop gradient, least nutrient loss was recorded in 1% slope gradient followed by 5% slope gradient, however highest was recorded in 10% slope gradient. Moreover, regarding soil amendments, minimum nutrient loss was recorded in control followed by the treatment where gypsum was applied whereas highest was recorded in the treatment where chemical fertilizer was applied. In case of interaction of slope gradient and soil amendment, minimum was recorded in control at 1% slope gradient followed by the gypsum at similar slope gradient while the maximum was recorded in chemical fertilizer treatment at 10% slope gradient (Fig.6).

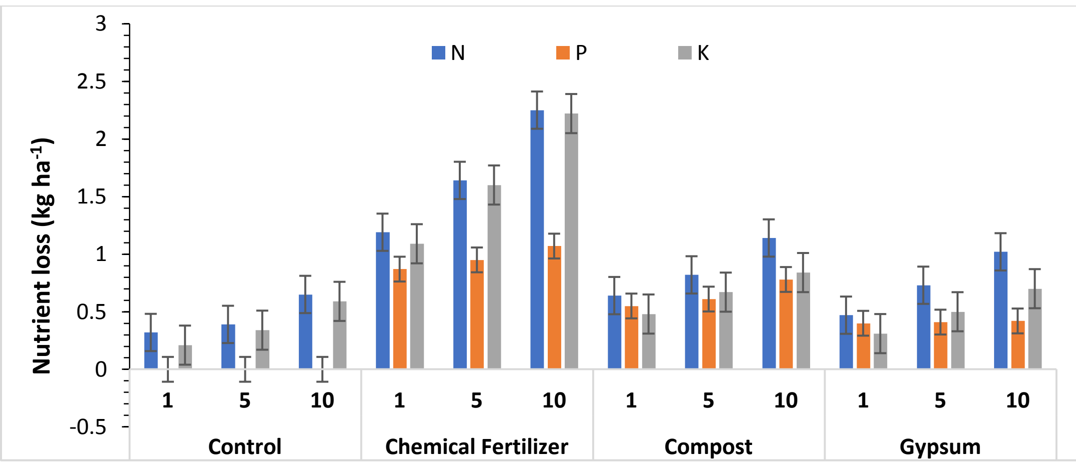


**Fig. 6.** Impact of soil amendments on average NPK loss (kg $ha^{-1}$) under different slope gradients during all study years. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

## NITROGEN LOSS AT DIFFERENT SLOPE GRADIENTS

Nitrogen loss was recorded in each and every year on all slope gradients after every rainfall greater than 20 mm. It was recorded that more losses were noticed with increase in slope gradient. Nitrogen losses were highest at the 10% slope gradient in the chemical fertilizer treatment, followed by the 5% and 1% slope gradients. Nitrogen loss increased significantly with the slope gradient. At the normal slope (S1= 1%), average nitrogen loss during all study years was measured at 1.19 kg/ha, whereas at the steep slope (S3=10%), it increased to 2.25 kg/ha in chemical fertilizer treated plots. The moderate slope (S2=5%) showed an intermediate value of 1.64 kg/ha (Fig. 7). The increased nitrogen loss on steeper slopes is likely due to higher runoff velocity and decreased infiltration rates. Nitrogen loss was decreased in compost treated plots followed by gypsum and control in all cropping seasons and slop gradients. Data was supported with the similar finding (16, 26, 27).

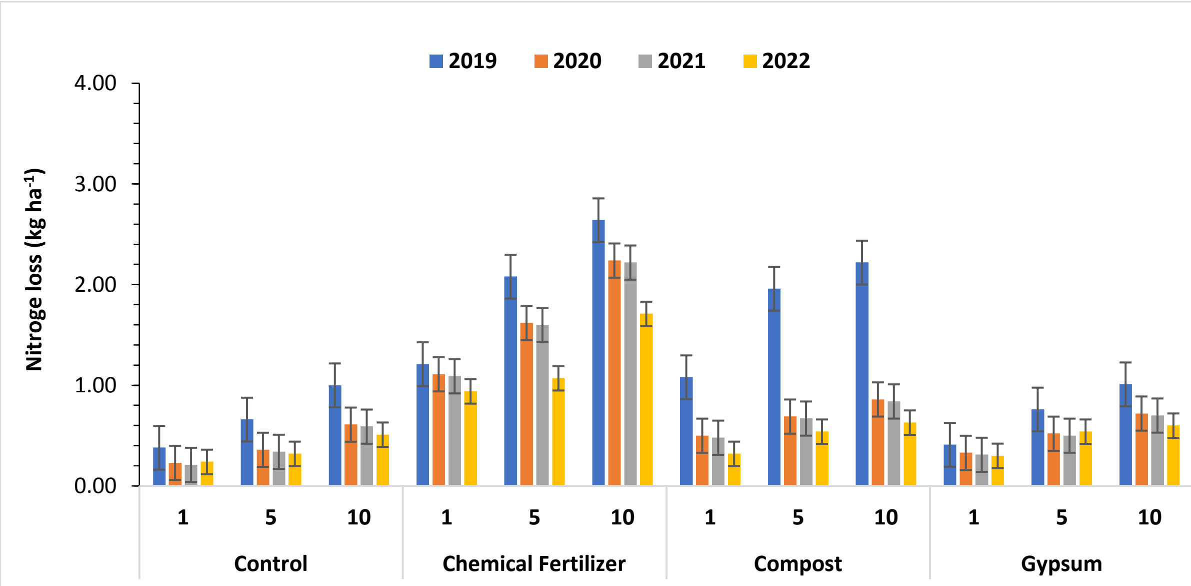


**Fig. 7.** Impact of soil amendments on Nitrogen loss (kg ha$^{-1}$) under different slope gradients. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

## PHOSPHOROUS LOSS AT DIFFERENT SLOPE GRADIENTS

Phosphorous loss was recorded in each and every year on all slope gradients after every rainfall greater than 20 mm. It was recorded that more losses were noticed as slope increases. Phosphorus losses were greatest at the 10% slope gradient under the chemical fertilizer treatment, followed by the 5% and 1% slope gradients. After chemical fertilizer P loss was decreased in compost treated plots followed by gypsum and control in all cropping seasons and slope gradients. Phosphorus loss also demonstrated a positive correlation with slope gradient. At the normal slope (S1=1%), average P loss during all study years was measured at 0.87 kg/ha, whereas at the steep slope (S3=10%), it increased to 1.07 kg/ha in chemical fertilizer treated plots. The moderate slope (S2=5%) showed an intermediate value of 0.95 kg/ha (Fig. 8). Less P loss was observed in compost followed by gypsum treated plots. The higher erosion rates and surface runoff on steeper slopes are likely responsible for the increased phosphorus loss. The amendments promoted soil aggregation and reduced the likelihood of erosion, thereby improving nutrient retention on steep slopes. Results were supported with the same finding by (28). In another study the increase in the nutrient uptake by gypsum application was attributed to improved soil physicochemical properties (4).

## POTASSIUM (K) LOSS AT DIFFERENT SLOPE GRADIENTS

Potassium loss was recorded in each and every year on all slope gradients after every rainfall greater than 20 mm. It was recorded that more losses were noticed as slope increases. Potassium losses were highest at the 10% slope gradient in the chemical fertilizer treatment, followed by the 5% and then the 1% slope gradients. After chemical fertilizer K loss was decreased in compost treated plots followed by gypsum and control in all cropping seasons and slope gradients as compared with chemical fertilizer treated plots. At the normal slope (S1=1%), average K loss during all study years was measured at 1.09 kg ha$^{-1}$, whereas at the steep slope (S3=10%), it increased to 2.22 kg/ha in chemical fertilizer treated plots. The moderate slope (S2=5%) showed an intermediate value of 1.06 kg/ha (Fig.9). Less K loss was observed in compost followed by gypsum treated plots. In a study it was reported that more nutrients loss was observed on control (bare plots) as compared to cultivated plots and these losses varies depending on land use types and practices (28).

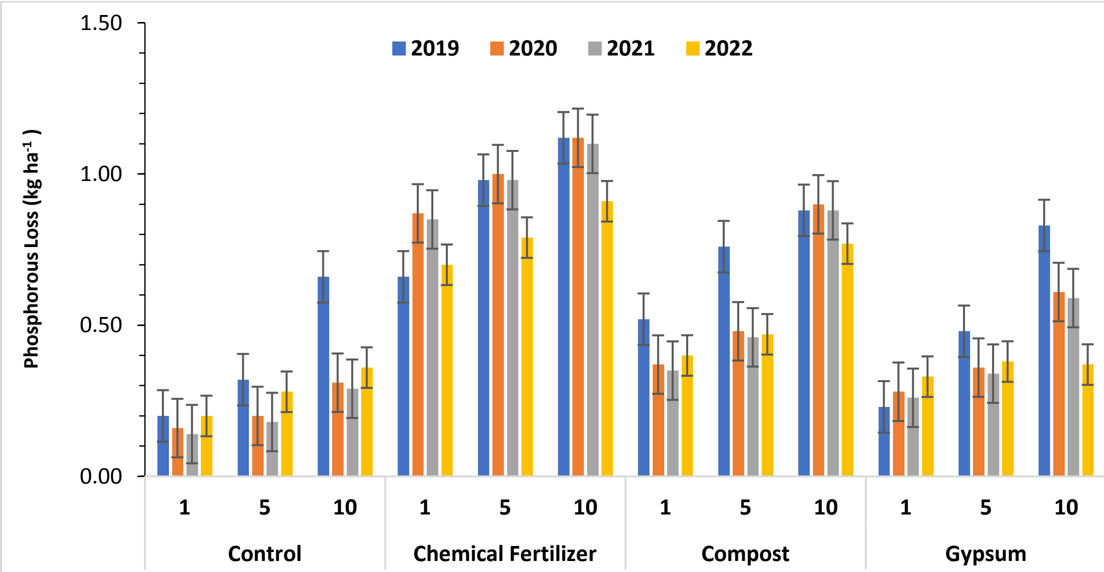


**Fig. 8**. Impact of soil amendments on Phosphorous loss (kg ha$^{-1}$) under different slope gradients. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

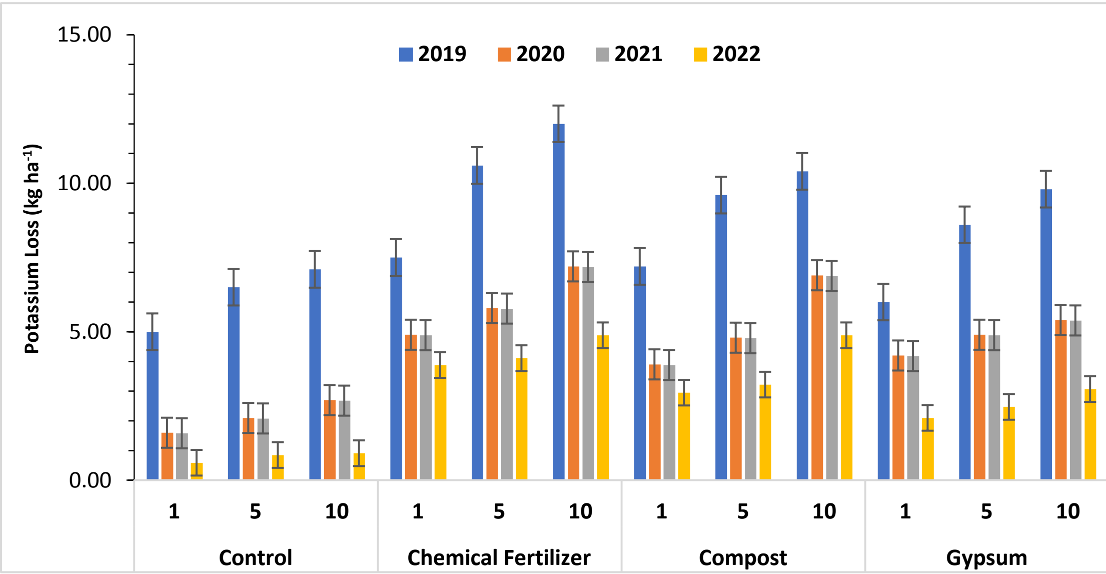


**Fig. 9.** Impact of soil amendments on Potassium loss (kg ha$^{-1}$) under different slope gradients. T=Treatments (T1= Control, T2= Chemical Fertilizer T3=Compost T4= Gypsum), S= Slope Gradients (S1:1%, S2:5%, S3:10 %)

The findings of this study have important implications for sustainable agriculture, especially in rainfed and sloping terrains. The significant reduction in runoff, sediment loss, and nutrient depletion through the use of soil amendments, particularly gypsum and compost, highlights the potential of these practices in improving soil health and water conservation. Reduced nutrient losses contribute to better fertilizer use efficiency, lowering input costs and minimizing environmental pollution from runoff. Moreover, enhanced moisture retention and reduced erosion directly support crop productivity and resilience under variable rainfall conditions. Adoption of such amendments can therefore play a critical role in promoting climate-smart agriculture, conserving natural resources, and sustaining long-term agricultural productivity in erosion-prone areas.

# CONCLUSION

Based on the analysis of four years of data, the study clearly demonstrates that gypsum, followed by compost, was most effective in reducing soil and water losses, thereby significantly minimizing nutrient depletion across all slope gradients. In terms of crop productivity, both chemical fertilizer and gypsum treatments resulted in higher grain and straw yields. However, gypsum and compost consistently outperformed other treatments in controlling runoff, sedimentation, and nutrient loss. These findings suggest that the combined application of gypsum or compost with chemical fertilizers can effectively mitigate erosion risks without compromising crop yield. Therefore, the integration of organic amendments, particularly gypsum and compost, into existing fertilization practices is recommended as a sustainable strategy to enhance soil conservation and maintain agricultural productivity in sloping and erosion-prone regions.

## Conflict of interest:

The authors declare no conflict of interest.

## Authors' contribution:

AM: Writing of original draft, conceptualization, conducted experiment and data analysis; OUR: Supervision; SI Reviewed the original draft; RK: Conceived the Idea, overall management of the work; MK, MUM & SA: Helped in data analysis; AB: Reviewed the final draft. All the authors reviewed the results and approved the final version of the manuscript.

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