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ORIGINAL ARTICLE

Impact of polyvinyl alcohol application and wheat straw mulching on soil loss and infiltration rate in semi-arid tropics

Mahesh Chand Singh[1] · Gaganpreet Singh[1] · Chetak Bishnoi[2] · Anurag Malik[2] · Nadhir Al-Ansari[3] · Mohamed A. Mattar[4]

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Abstract
A study was conducted at Punjab Agricultural University, Ludhiana, Punjab, with the aim of monitoring soil loss and infiltration rate in loamy sand soil. The study focused on the effects of applying polyvinyl alcohol (PVA) and mulch under simulated rainfall conditions. The experimental setup involved testing three levels of PVA (0.5%, 0.75%, and 1.0%), one level of wheat-straw mulch (600 g/m^2), and a Control treatment (untreated soil). Each of these treatments was replicated four times. The lowest soil loss (20.9 g/m^2) was recorded under the 1.0% PVA treatment, while the highest (120.1 g/m^2) was seen under the 0.5% PVA treatment. The 1.0% PVA treatment showed a significant reduction in soil loss compared to the 0.5% PVA, 0.75% PVA, mulch, and Control treatments, with reductions of approximately 82.6%, 45.1%, 81.2%, and 89.6%, respectively. Regarding infiltration rates, the Control treatment exhibited the lowest rate (2.4 cm/h), while the 1.0% PVA treatment displayed the highest rate (9.6 cm/h). Additionally, the use of mulch led to a 44.7% reduction in soil loss compared to the treatment without mulch, likely due to the mitigated impact of raindrops. The infiltration rate was significantly higher (4.8 cm/h) under the mulched treatment compared to the unmulched treatment (2.4 cm/h). Overall, the application of PVA and mulch resulted in a drastic reduction in soil loss, likely attributable to the enhanced stability of soil aggregates, improved infiltration rate, and reduced runoff.

Keywords Infiltration · Mulch · PVA · Soil erosion · Soil aggregates

Introduction

Soil loss due to splash erosion is influenced by two main components: the velocity and impact force of raindrops as they strike the soil surface, along with the resulting kinetic energy (Angulo-Martínez et al. 2012). Additionally, various other factors play crucial roles in this erosional process. These include the soil texture, structure, permeability, porosity, moisture content, and organic matter content, as highlighted by Bryan (1974). Splash erosion holds particular significance in altering landscapes, especially in arid regions, as indicated by Boroghani et al. (2012). The kinetic energy generated by raindrops impacting the exposed land surface causes the disintegration of soil aggregates and

✉ Mahesh Chand Singh
msrawat@pau.edu

✉ Nadhir Al-Ansari
nadhir.alansari@ltu.se

✉ Mohamed A. Mattar
mmattar@ksu.edu.sa

Gaganpreet Singh
gagandhamrait07@gmail.com

Chetak Bishnoi
chetakbishnoi@pau.edu

Anurag Malik
amalik19@pau.edu

1 Department of Soil and Water Engineering, Punjab Agricultural University, Ludhiana, Punjab 141004, India

2 Punjab Agricultural University, Regional Research Station, Bathinda, Punjab 151001, India

3 Department of Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, 97187 Lulea, Sweden

4 Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia

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harms its structure. Notably, finer soil particles are more easily transported by runoff, contributing to soil loss. The disintegration of soil aggregates is directly linked to the impact of raindrops falling on the land surface. This process obstructs soil pores by dispersing finer particles, ultimately forming a surface crust. This phenomenon, described by Lado et al. (2004), further accentuates the complexity of splash erosion and its role in modifying landscapes.

A crust refers to a thin layer of soil with a higher bulk density, finer pores, and lower hydraulic conductivity compared to the soil beneath it (Wakindiki and Ben-Hur 2002; Assouline 2004). This crust forms primarily due to the sealing of soil pores by finer particles splashed onto the surface, substantially reducing the soil infiltration rate (Ben-Hur et al. 1998; Li et al. 2005). Consequently, this reduction in infiltration rate leads to increased runoff and flooding potential (Moore and Singer 1990; Wuddivira et al. 2009) and decreases the capacity of the soil to store water (Le Bissonnais et al. 1998). Additionally, the presence of this crust hinders seedling emergence, requiring greater force for seedlings to break through the crust (Souty et al. 1992; Mukhopadhyay et al. 1997). Given these consequences, it becomes crucial to enhance the infiltration rate to mitigate soil loss through controlled surface runoff and erosion. Moreover, mitigating splash erosion by reducing soil erodibility or the impact of raindrops (Bradford et al. 1987) is of significant importance. Enhancing infiltration rates and reducing splash erosion can be achieved by applying polymers and mulching on the soil surface.

Polymers have the potential to enhance soil infiltration by improving hydraulic conductivity and porosity (Brandsma et al. 1999), increasing water holding capacity (Shanmuganathan and Oades 1982), and reducing splash/raindrop erosion (Wood and Oster 1985). Specifically, among various polymers and soil conditioners, polyvinyl alcohol (PVA) stands out for its ability to improve soil aggregate stability and structure. This enhancement is achieved by boosting infiltration rates, reducing runoff generation, and preventing surface crusting. PVA, especially in low concentrations, plays a significant role in enhancing the stability of soil aggregates, as highlighted by Sen et al. (1995) and Kukal et al. (2007). Patcharapreecha et al. (1993) have emphasized the effectiveness of PVA in stabilizing aggregates, particularly in sandy soil, thereby enhancing the physical properties. Moreover, according to Yakupoglu et al. (2019), polymers like PVA and polyacrylamide (PAM) exhibit heightened efficiency in controlling soil erosion when the soil aggregates exceed 6.4 mm in size.

In a study conducted by Tümsavaş and Tümsavaş (2011), the impacts of varying polyvinyl alcohol (PVA) application rates (0, 1.85, 3.7, and 5.55 kg/ha) on soil loss, runoff, and drainage water were investigated under simulated rainfall conditions for a duration of one hour, with an intensity of 61 mm/h. The results indicated a decrease in surface runoff and soil loss, but an increase in drainage water with higher PVA application rates. Mulching the soil surface is recognized as an effective technique for controlling soil erosion and enhancing land surface conditions (Parsakhoo et al. 2019). The application of mulch on the soil surface serves to mitigate soil loss caused by splash erosion, reducing the impact force and energy of raindrops hitting the soil surface (Parsakhoo et al. 2019). Additionally, it aids in minimizing crusting (Gicheru 2004), augmenting organic matter content in the soil, and enhancing soil aggregation (Sur and Ghuman 1994). As proposed by Tümsavaş (2017), in areas highly susceptible to erosion, the application of wheat straw mulch at a rate of at least 500 g/m^2 on the soil surface is recommended.

In the realm of investigating infiltration rate, runoff, and soil erosion/loss amidst diverse circumstances encompassing varying rainfall intensities, soil compositions, and slopes, rainfall simulators stand out as prevalent instruments (André and Anderson 1961; Cerdà et al. 1997; Grismer 2012; Parsakhoo et al. 2012; Aksoy et al. 2012; Wang et al. 2022; Zhu et al. 2022; Zhao et al. 2023; Bai et al. 2024). These instruments are capable of delivering consistent rainfall dispersion, mimicking raindrop sizes accurately, and providing kinetic energy within a broad spectrum of rainfall intensities that mirror natural rain patterns (Navas et al. 1990; Munster et al. 2006). The raindrop sizes in natural rainfall typically fall between the range of 0.5–6 mm. Conversely, the average raindrop diameter varies between 2 and 3 mm (Laws and Parsons 1943; Dunne et al. 1980). Additionally, natural raindrops necessitate a drop height of approximately 3.0–3.7 m (10–12 feet) to achieve terminal velocities, generating kinetic energy akin to raindrops in authentic rainfall conditions (Bryan 1974). However, replicating this height accurately in real-world field settings poses considerable challenges, rendering it impracticable for field investigations (Aksoy et al. 2012). Consequently, the drop height is subject to alteration based on the pressure or discharge rate of the drop formers in relation to reaching terminal velocity.

In this specific study, a laboratory experiment was conducted to evaluate soil loss under simulated rainfall settings while maintaining a drop height of 3.6 m between the drop-formers and the top surface of the soil columns. The drop size varied within the range of 2–4 mm.

Numerous studies have been conducted globally to estimate soil erosion using various methods, including the application of polymers and mulch. However, there has been limited research focusing on controlling soil erosion loss and infiltration rates specifically using polyvinyl alcohol (PVA) and wheat straw mulch in loamy sand soils over the past few decades. To address this gap, this study evaluates soil erosion/loss and infiltration rates by applying different concentrations of PVA (0.5%, 0.75%, and 1.0%) and wheat straw mulch under simulated rainfall conditions in loamy sand soil.

Materials and methods

Description of study site

A study was conducted at the Research Farm (S.D. Khepar Laboratories) of the Department of Soil and Water Engineering, Punjab Agricultural University (PAU), Ludhiana. The purpose of this experiment was to investigate the impacts of Polyvinyl Alcohol (PVA) application and mulching on soil loss and infiltration rate under simulated rainfall conditions. The research site is situated at 30° 54′ N latitude and 75° 48′ E longitude, with an elevation of 247 m above sea level. Figure 1 provides a map of the study area.

The region features a semi-arid, subtropical climate, characterized by very hot summers (April–June) and cold winters (December–January). The annual temperature ranges significantly, with summer temperatures exceeding 38 °C and reaching up to 47 °C. In contrast, winter temperatures can drop below 4 °C, with occasional frost. The dominant winds during this period are from the northeast. The area receives an average annual rainfall of 680 mm, with 75–80% occurring between June and September. Winter precipitation is minimal and typically results from cyclonic activity due to western disturbances. The region experiences four distinct seasons namely spring (March–May, pleasant), summer (June–August, warm), autumn (September–October, mildly cold), and winter (November–February, extremely cold).

Soil sampling

Soil samples were gathered from the uppermost layer (0–15 cm) from ten distinct locations identified by geotags within the Research Farm of the Department of Soil and Water Engineering at PAU Ludhiana. These collected samples were meticulously blended to create composite samples, intended for the soil columns allocated in

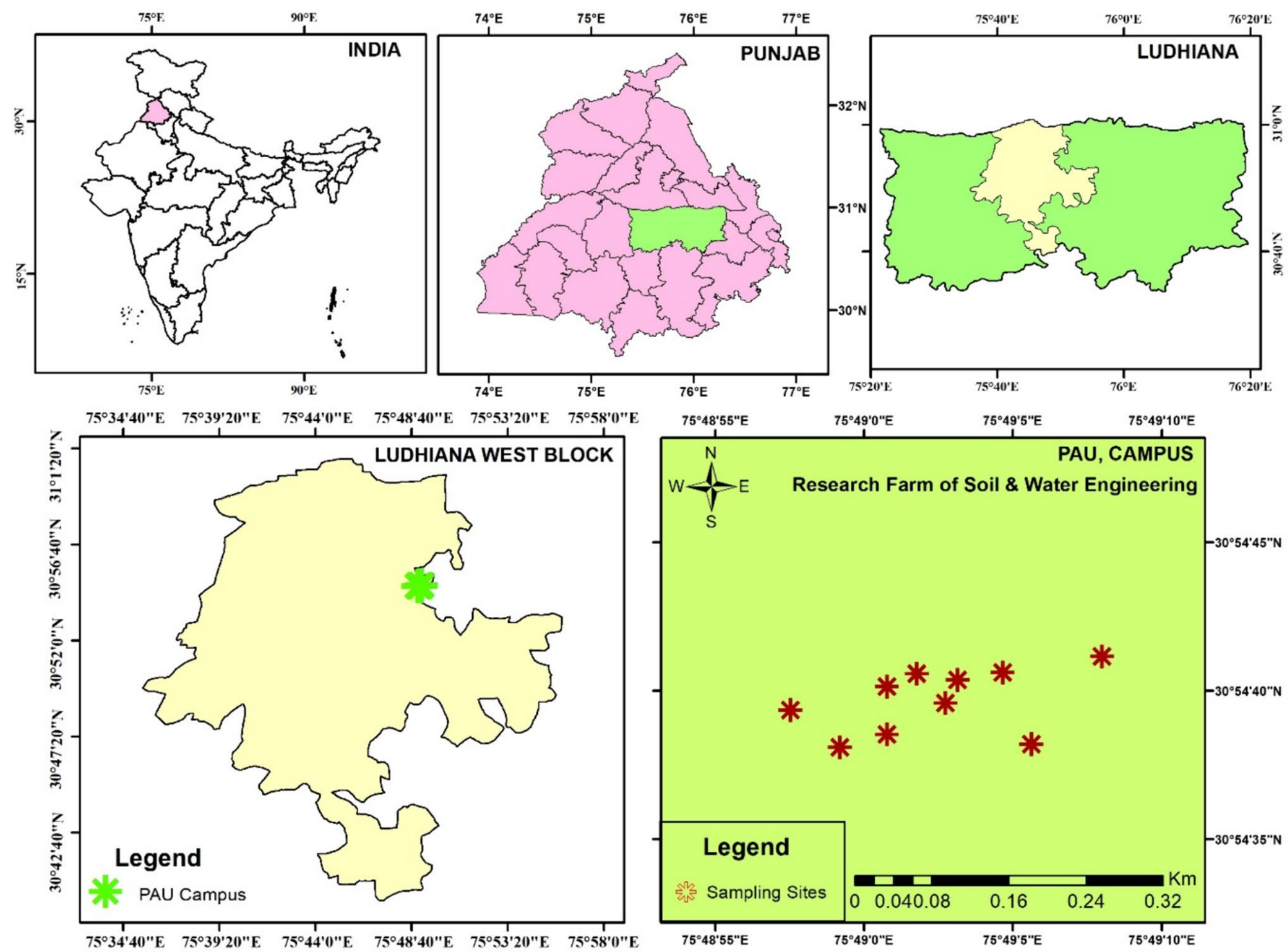


Fig. 1 Study area map

rectangular trays. Subsequently, this mixture underwent a comprehensive analysis to determine various physico-chemical attributes including texture, pH, moisture content, organic carbon levels, electrical conductivity (EC), phosphorus, and potassium. The composite soil sample of the site exhibited a loamy sand texture as per classification by USDA, having 83.3% sand, 4.4% silt, and 12.3% clay without the addition of PVA, as detailed in Table 1. The other parameters of composite soil including EC, pH, and organic carbon content are given in Table 1.

Table 1 Characteristics of the study soils

Parameter	Value
Sand (%)	83.3
Silt (%)	4.4
Clay (%)	12.3
Textural class (USDA)	Loamy sand
pH	8.4
EC (mhos/m)	0.21
Moisture content on dry basis (%)	15.7
Organic carbon (%)	0.27
Phosphorus (kg/acre)	3.2
Potassium (kg/acre)	91

Description of raindrop simulator

A rainfall simulation setup was meticulously arranged to conduct the experiment as depicted in Fig. 2. This setup involved configuring a rainfall simulator with a comprehensive system, including five multiple drop formers, all interconnected to a water reservoir within the simulator assembly (Fig. 2). The objective was to generate a diverse spectrum of raindrops falling within the size range of 2–4 mm. To achieve this, the rainfall simulators were strategically positioned at a height of 3.6 m above the upper surface of the soil columns directly beneath them. This positioning was critical to ensure that the raindrops could achieve approximately 75–95% of their terminal velocity, relative to their respective sizes, as described by Bryan in

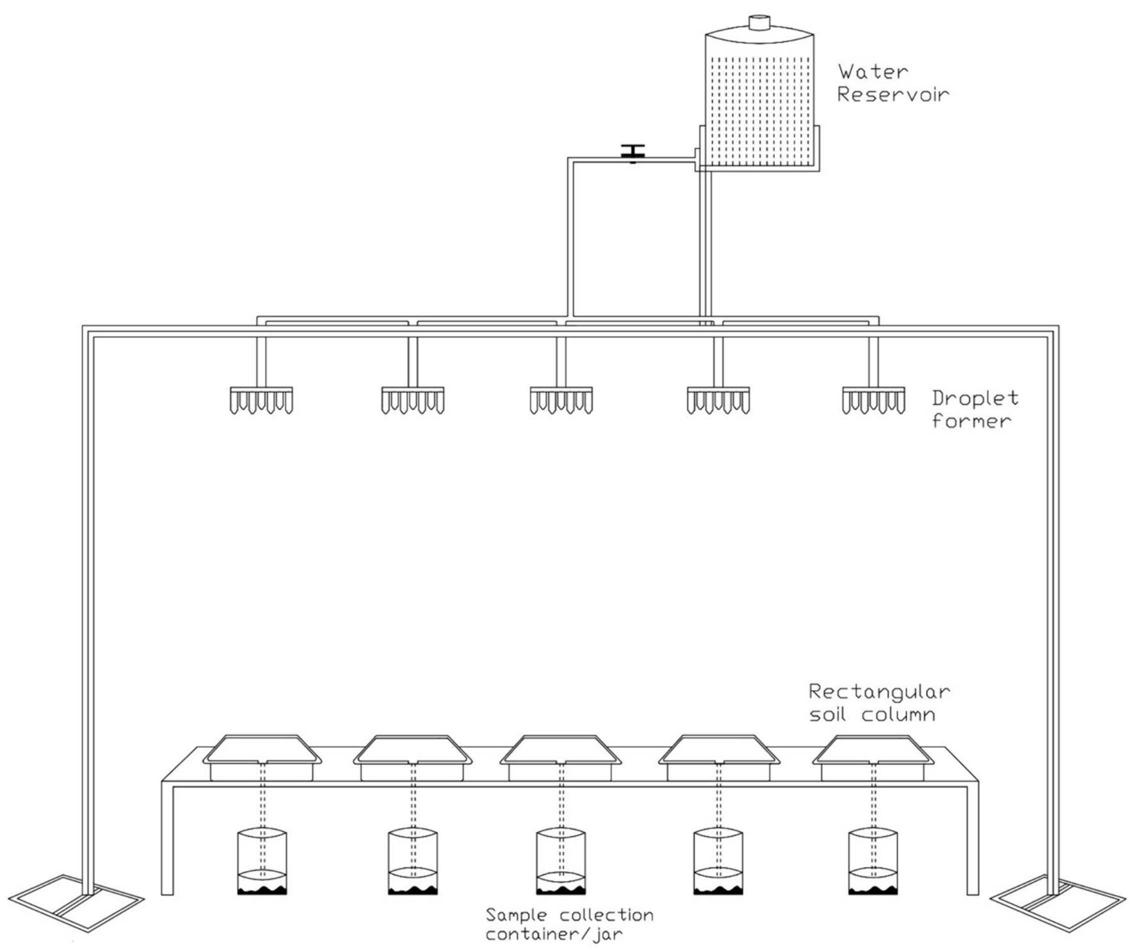


Fig. 2 Schematic of rainfall simulator

1974. The artificial raindrops were created using standard tube well water to replicate natural rainfall conditions.

Preparation of soil columns

Soil columns were prepared for various treatments by accurately measuring and utilizing the predetermined weight of loamy sand soil. The soils were then meticulously packed into rectangular columns, achieving a specific bulk density of approximately 1.55 g/cm^3 through careful compaction using a wooden log. Afterward, the soil in each column underwent a saturation process with water, allowing drainage until the water vanished entirely from the top surface. Subsequently, predetermined quantities of PVA in powder form were uniformly distributed onto the top surface of the soil columns. This application was followed by a delicate spray of water to prevent flooding and to facilitate the settling of the PVA. The soil columns were left to settle undisturbed for a duration of 18–24 h. To simulate natural conditions, the soil columns were inclined at an angle of around 6–7%, promoting runoff in a single direction. This design also facilitated the collection of runoff samples for analysis. The calculation of PVA doses (0.5%, 0.75%, and 1.0%) was determined based on the weight of soil utilized in each respective column for a specific treatment.

Experimental treatments

The experiment comprised a total of five distinct treatments, encompassing Control/untreated soil as one of them. These treatments consisted of varying levels of PVA application (0.5%, 0.75%, and 1.0%) on the tilled surface of the soil columns. Additionally, wheat straw mulch was applied at a specific rate of 600 g per square meter, evenly spread on the tilled soil surface. Another treatment involved Control/untreated tilled soil. Following the application of PVA, the tilled soil surface underwent a designated air-drying period, lasting approximately 18–24 h, before being exposed to simulated raindrops.

Measurement of soil loss and infiltration rate

The study involved the preparation of soil columns with specific dimensions (36 cm × 30 cm × 12 cm), which were then given a slope of approximately 3.3 degrees. Subsequently, these soil columns were subjected to simulated raindrops for a duration of 10 min. Runoff water resulting from this simulation was collected in containers or jars placed directly beneath the soil columns as depicted in Fig. 3a. The collected water was allowed to settle, enabling the soil to settle at the bottom of the containers. Clearwater was then removed through a repetitive process until no further water remained. Following this, the wet soil remaining in the containers underwent oven drying for approximately 24 h (at a temperature of 105 °C) to determine the dry weight of the soil. To calculate the infiltration rate within the soil columns, cylindrical metal cores with an inner diameter and height of 7.8 cm and 7.0 cm, respectively, were employed. The infiltration rates for various treatments were also calculated utilizing a double-ring infiltrometer under field conditions. This involved following a standard procedure and comparing the resulting infiltration rates with those obtained from the cores installed in the soil columns. The outer rings of the infiltrometer had a height and inner diameter of 29.8 cm and 58.8 cm, respectively, while the inner concentric rings had dimensions of 29.8 cm and 29.5 cm, respectively, as illustrated in Fig. 3b.

Statistical analysis

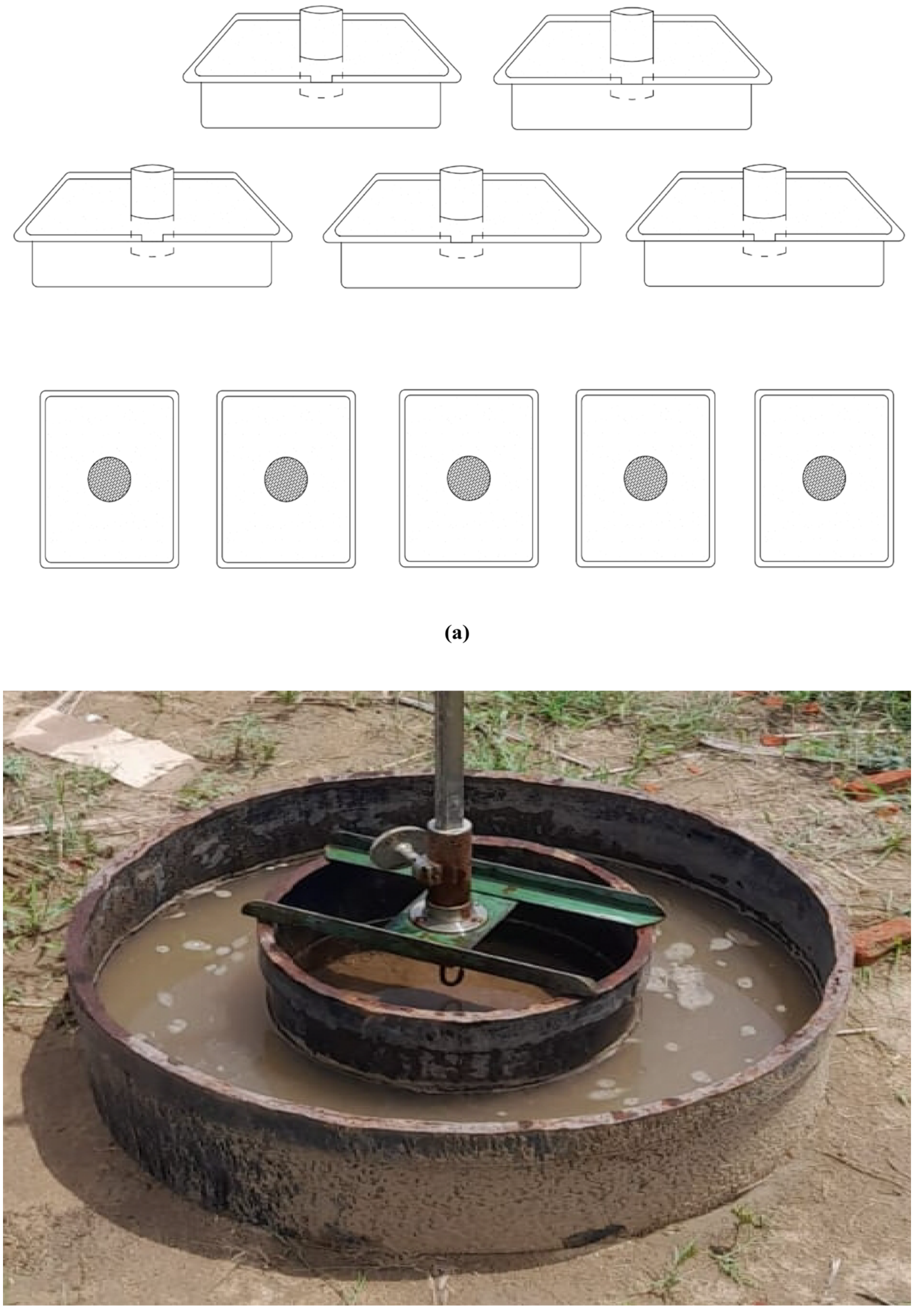
The process involved conducting a thorough statistical examination of the dataset pertaining to soil loss, which was gathered through various treatments within a randomized block design. This analysis was conducted utilizing the Statistical Package for the Social Sciences (SPSS) software.

Results and discussion

Effect of PVA application on soil loss and infiltration rate

According to existing literature, the use of PVA as a soil conditioner demonstrates its capacity to enhance soil infiltration, characterized by improved porosity and hydraulic conductivity, as well as positively affecting the physical properties of the soil, stability of soil aggregates, water holding capacity, and reduction of splash erosion (Shanmuganathan and Oades 1982; Wood and Oster 1985; Patcharapreecha et al. 1993; Sen et al. 1995; Brandsma et al. 1999; Kukal et al. 2007). In the specific case of loamy sand soil, the application of PVA significantly reduced soil loss, primarily attributed to an increase in infiltration rate and a decrease in surface runoff. Among the various PVA treatments (0.5%, 0.75%, and 1.0%), there was a notable reduction in soil loss as the PVA application increased from 0.5 to 1.0% (Fig. 4a). The lowest soil loss was recorded under the 1.0% PVA treatment, while the highest was observed in the control/untreated soil treatment, mainly due to increased stability of soil aggregates, improved water holding capacity, and reduction of splash erosion due to PVA application. These results are in close agreement with the observations of Kukal and Sarkar (2010), Tümsavaş and Tümsavaş (2011), and Yakupoglu et al. (2019), and the same can be seen in Fig. 4a. This establishes a clear inverse relationship between the PVA dose and soil loss. In a study

Fig. 3 Measurement of infiltration in **a** soil columns using metal cores and **b** under field conditions using double ring infiltrometer



(a)

(b)

investigating the effect of PVA application (0.1% and 0.5%) on soil loss due to splash erosion in sandy loam soil, Kukal and Sarkar (2010) reported the lowest soil loss (41.2 g/m^2) under the 0.5% PVA treatment and the highest (275.9 g/m^2) under the control treatment.

Furthermore, Tümsavaş and Tümsavaş (2011) reported a 28.8% reduction in soil loss through PVA application at a rate of 3.7 kg/ha. The results of the present study align with those reported by several researchers in the past. However, variations in soil loss were observed in different studies conducted by various authors, depending on factors such as soil types, PVA application rates, land slope, and other parameters. The reductions in soil loss under the 1.0% PVA treatment were approximately 82.6%, 45.1%, 81.2%, and 89.6% compared to the 0.5% PVA, 0.75% PVA, mulched, and unmulched treatments, respectively (Table 2). Similarly, under the 0.75% PVA treatment, reductions of about 68.2%, 65.7%, and 81.1% in soil loss were observed compared to the 0.5% PVA, mulched, and unmulched treatments, respectively. In the 1.0% PVA treatment, soil loss reductions of 7.3% and 44.7% were recorded compared to the 0.5% PVA and unmulched treatments, respectively. Notably, the

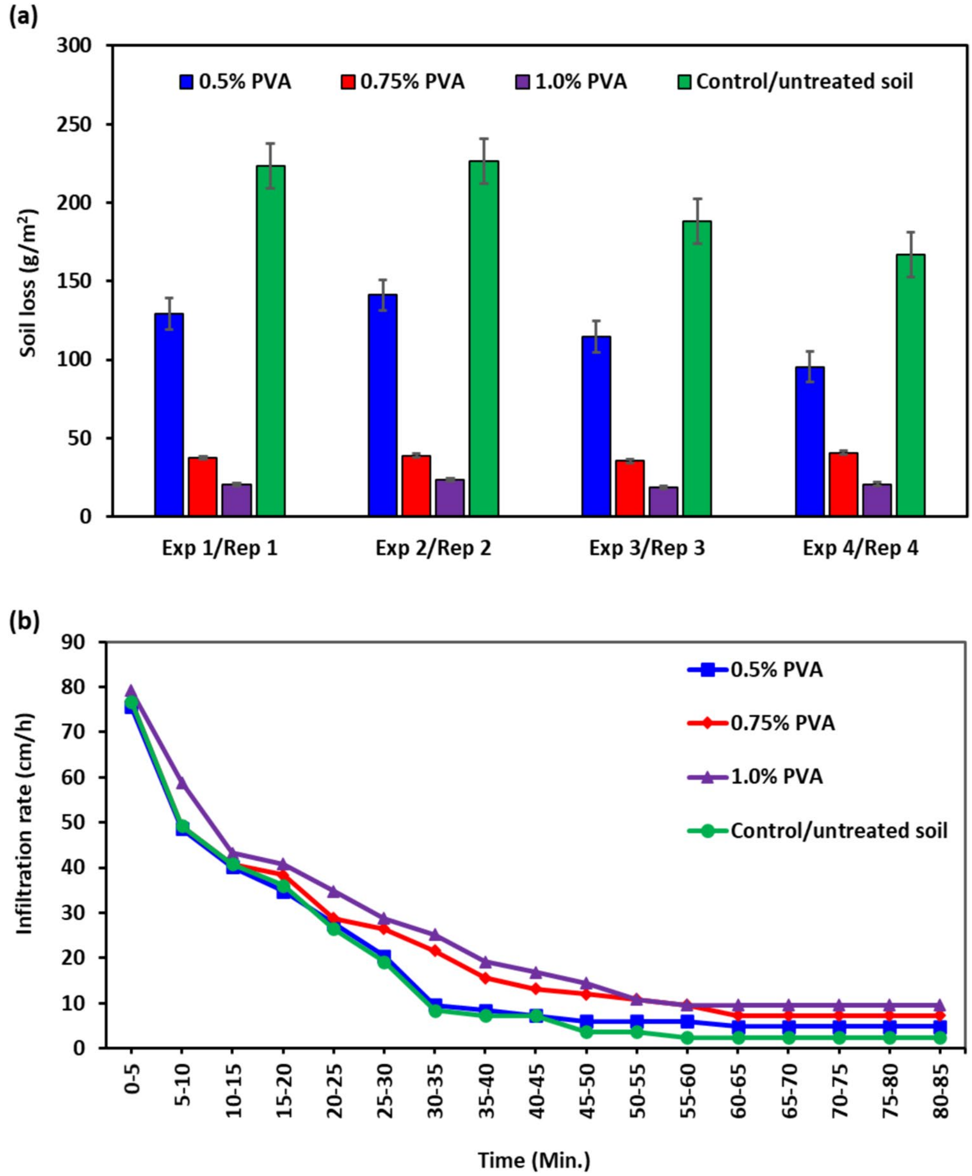


Fig. 4 Variation in **a** soil loss and **b** infiltration rate in relation to PVA application

Table 2 Soil loss and basic infiltration rate of loamy sand soil as affected by application of polyvinyl alcohol (PVA)

Treatment	Soil loss (g/m^2)	Infiltration rate (cm/h)
0.5% PVA	120.1	4.8
0.75% PVA	38.1	7.2
1.0% PVA	20.9	9.6
Control (untreated soil)	201.2	2.4
Mean	95.1	6.0
LSD (0.05)	S	S

soil loss under the 0.5% PVA treatment was 40.3% lower compared to the unmulched treatment. Thus, among all five treatments, the 1.0% PVA treatment was found to be the most effective, followed by the 0.75% PVA and mulching.

The experimental results indicated a significant reduction in soil loss with the application of PVA, particularly in the transitions from 0.5% to 0.75%, 0.5% to 1.0%, and 0.75% to 1.0%, possibly due to enhanced stability of soil aggregates and improved infiltration rate (Sen et al. 1995; Kukal and Sarkar 2010). Recent research by Yakupoglu et al. (2019) also confirmed the effectiveness of PVA in minimizing soil loss and increasing the size of soil aggregates. Past research also suggests a decrease in surface runoff and soil loss with PVA application (Patcharapreecha et al. 1993; Tümsavaş and Tümsavaş 2011; Yakupoglu et al. 2019). Tümsavaş and Tümsavaş (2011) reported a 28.8% reduction in runoff and a 34.8% reduction in soil loss with PVA-treated soil (3.7 kg/ha) compared to untreated soil, accompanied by a 161.1% increase in drainage water. The variations in soil loss in PVA treatments and control/untreated soil across different experiments/replications are presented in Fig. 4a.

Infiltration refers to the soil's ability to allow water to penetrate through its profile, enabling temporary water storage for use by crops. The infiltration rate indicates how quickly water penetrates the soil. A low infiltration rate can result in ponding (flooding) in flat lands, surface runoff, and soil erosion in sloped lands. A reduced infiltration rate decreases soil moisture availability for plant growth and groundwater recharge potential. Therefore, enhancing soil infiltration rate up to an optimal limit is desirable. Among the PVA treatments, the lowest (4.8 cm/h) and highest (9.6 cm/h) infiltration rates were recorded under the 0.5% and 1.0% PVA treatments, respectively. In comparison, across all treatments, the lowest (2.4 cm/h) and highest (9.6 cm/h) infiltration rates were observed under the control/untreated soil and 1.0% PVA treatment, respectively. These results closely align with the observations of Kukal and Sarkar (2010), which is quite clear from Fig. 4b. Overall, the baseline infiltration rate significantly increased with the application of PVA. The infiltration rate was highest for the 1.0% PVA treatment, followed by the 0.75% PVA, 0.5% PVA, mulched, and untreated soil treatments. The baseline infiltration rates for mulched and 0.5% PVA treatments were comparable. The baseline infiltration rate under the 1.0% PVA treatment was 100%, 33.3%, 100%, and 300% higher compared to the 0.5% PVA, 0.75% PVA, mulched, and control treatments, respectively (Table 2). The infiltration rate under the 0.75% PVA treatment was 50%, 50%, and 200% higher compared to the 0.5% PVA, mulched, and control treatments, respectively. Previous research also indicates an increase in infiltration rate with PVA application (Sur and Ghuman 1994; Gicheru 2004; Kukal and Sarkar 2010) due to the prevention of soil crusting and enhanced aggregate formation. Consequently, PVA can be used as a soil conditioner to mitigate soil loss and improve infiltration rate. Moreover, it is easily accessible in local markets and provides immediate results. The variation in soil loss in different experiments/replications is illustrated in Fig. 4a, while the variation in infiltration rates for all treatments, except mulch, is presented in Fig. 4b.

Effect of mulching on soil loss and infiltration rate

In accordance with findings reported in various scientific sources (Edwards et al. 2000; Parsakhoo et al. 2019), the literature suggests that mulch serves to absorb the kinetic energy of raindrops, thus mitigating soil loss caused by splash erosion. Additionally, it aids in enhancing soil infiltration rates and reducing soil loss, potentially attributed to the diminished severity of crusting on the soil surface (Rao et al. 1998). Notably, raindrop impact and flowing water can easily detach coarse-textured soil, though its transportation is less facile. Conversely, fine-textured soil resists detachment but can be transported more easily.

In the current study, the application of wheat straw mulch resulted in a substantial reduction (approximately 44.7%) in soil loss through splash erosion compared to the untreated, tilled soil (referred to as Control). This reduction is presumably due to the raindrop force-absorbing property of the mulch, thereby reducing soil detachment and subsequent transportation. Soil loss measurements for the mulched and Control treatments were recorded at 111.3 g/m^2 and 201.2 g/m^2, respectively (Table 3). Tümsavaş (2017) had previously reported a significant 98% reduction in soil loss through the surface application of wheat straw mulch (at a rate of 500 g/m^2). Similarly, Mannering and Meyer (1963) found reduced soil loss attributable to a decrease in raindrop impact on the soil surface due to the presence of wheat straw mulch, resulting in increased infiltration rates by avoiding soil crusting.

In contrast, infiltration rates showed an opposite trend, with a marked 100% increase in the basic infiltration rate observed with wheat straw mulch compared to the Control/untreated soil. In the present study, the infiltration rate was significantly higher (4.8 cm/h) under the mulched treatment compared to the unmulched/untreated soil (2.4 cm/h). Gholami et al. (2014) also noted reductions in raindrop erosion, crusting, runoff, sediment yield, and soil loss, accompanied by increased infiltration and drainage rates through the use of barley straw mulch on the soil surface. Moreover, as per Wang et al. (2022), employing wheat straw mulch (at a length of 3–5 cm) on sloping lands effectively increased infiltration rates and decreased runoff, consequently lowering soil loss and sediment yield.

Hence, mulch exhibits the potential to reduce soil loss by improving infiltration rates and decreasing runoff. This observation aligns with findings from previous researchers (Mannering and Meyer 1963; Sur and Ghuman 1994; Gicheru 2004; Parsakhoo et al. 2019; Wang et al. 2022). Nevertheless, caution should be exercised concerning potential insect-pest infestations associated with mulch use, warranting consideration of alternative measures such as PVA application over vegetative mulch. Figure 5a and

Table 3 Soil loss and basic infiltration rate of loamy sand soil as affected by mulching

Treatment	Soil loss (g/m^2)	Infiltration rate (cm/h)
Mulched	111.3	4.8
Unmulched	201.2	2.4
Mean	156.2	3.6
LSD (0.05)	S	S

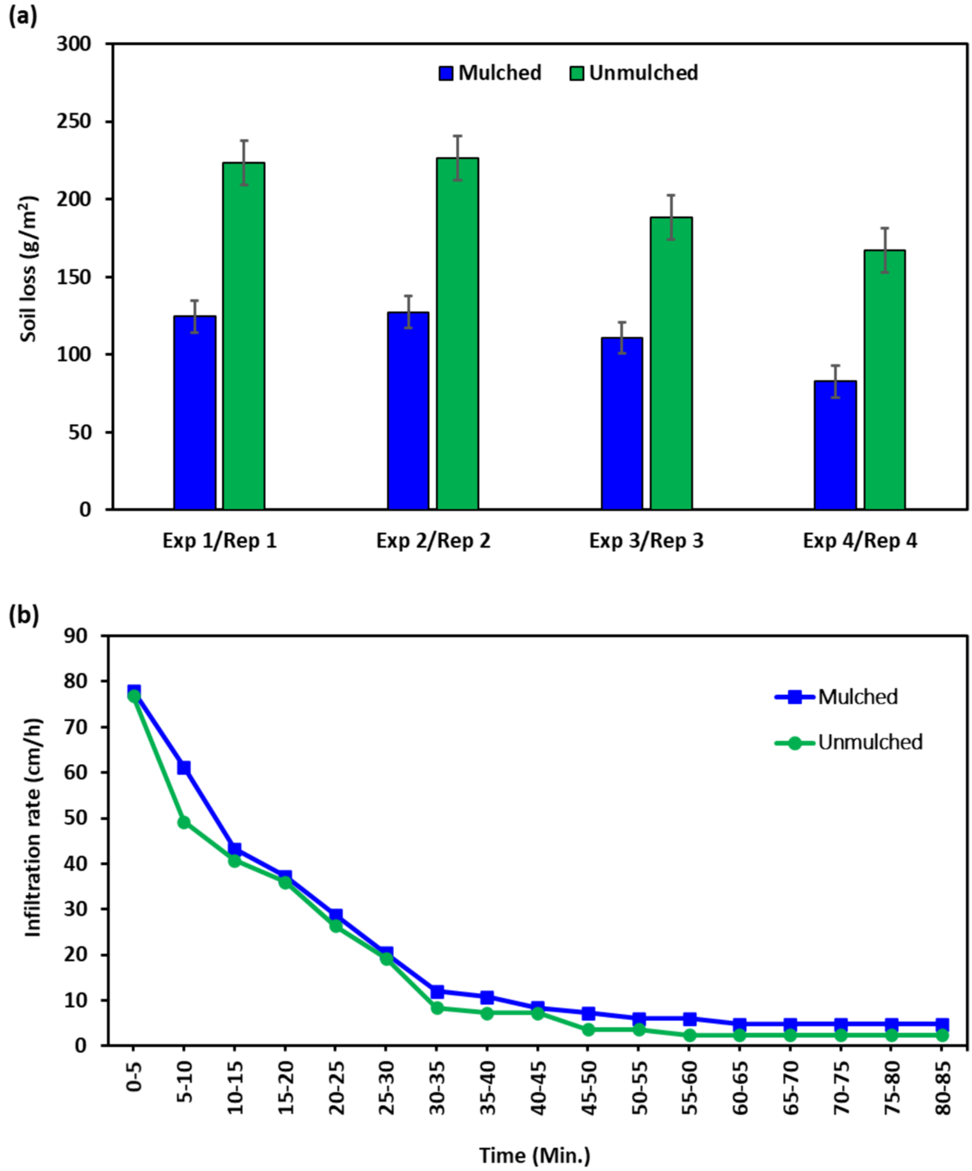


Fig. 5 Effect of mulching on **a** soil loss and **b** infiltration rate

b visually represent soil loss and variations in infiltration rate across different treatments. The results of this study unequivocally establish a close correlation between soil loss, surface crusting due to raindrop/splash erosion, soil aggregate stability, infiltration rate, and runoff. Armed with this understanding, proactive steps can be taken to mitigate soil loss by enhancing soil aggregate stability and infiltration rate, primarily through the judicious use of PVA (preferably) and wheat straw mulch.

Conclusions

The investigation demonstrated that utilizing Polyvinyl Alcohol (PVA) at concentrations of 0.75% and 1.0% proved to be the most effective method for reducing soil loss and enhancing infiltration rates. In the context of loamy sand soil, surface application of wheat straw mulch at a rate of 600 g/m^2 was determined to be marginally more effective in reducing soil loss when compared to the 0.5% PVA treatment. However, both the 0.5% PVA treatment and mulching exhibited similar enhancements in infiltration rates. The significant reduction in soil loss with both PVA and mulching can be attributed to the improved stability of soil aggregates, heightened infiltration rates, and reduced runoff. Considering the findings, PVA application may be the preferable choice due to concerns regarding potential insect-pest infestation associated with the use of vegetative mulch. Additionally, PVA stands out for its easy availability, user-friendly application, and rapid effectiveness.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest No conflict of interest.

Ethical approval Experimental research and field studies on plants (either cultivated or wild), including the collection of plant material, must comply with relevant institutional, national, and international guidelines and legislation.

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