Three-dimensional structure of preferential flow and its influencing factors in Agricultural area of Sheikhupura, Pakistan

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[Abstract]: Preferential flow is the Movement of water through specific pathways in soil rather than a more uniform flow through the soil structure. Because of soil heterogeneity, such as fractures, root channels, or wormholes, these preferential flow pathways frequently form. Particularly with depth in the soil, this fractal pattern can make it challenging to understand and describe the behavior of preferred flow routes. For accurate water and solute transport modelling and forecasting in the subsurface, it is need of hour to comprehend and describe the growth and evolution of preferential flow routes. In present study various methodologies have been utilized including field observations, soil samples, and imaging techniques including Origin Lab Pro, and Sketchup, to examine the three-dimensional structure of the preferred flow. We built a three- dimensional map of the favored flow pathways and examined their distribution patterns using data from various agricultural land areas. This study was carried on an adaptive research farm in Pakistan's Sheikhupura. In this study, results have been represented in a 3D representation to better understand the preferential flow. Four 120 * 120 cm plots were chosen, and on four plots, a dye tracing experiment was carried out to confirm the solute and water's preferred flow patterns. Data has been analyzed in Origin Lab to create 3D graphs and tables and used Sketchup-2021 Pro to create 3D images. According to the water flow patterns discovered in this study, preferred flow is strongest at the higher site free of compaction, where macro-pores continuity is preserved. Due to the compaction impact, the micro-porosity decreased, and it grew weaker on the lower side. The results demonstrate that preferential flow is most prominent in areas with minimal compaction and a preserved continuity of macro-pores. Conversely, the impact of compaction leads to a decrease in micro-porosity and weaker preferential flow patterns in compacted regions. Moreover, this study reveals how compaction and subsequent recovery processes influence soil's susceptibility to water flow and surface runoff. By presenting comprehensive 3D representations, this research offers a superior understanding of the creation and evolution of water flow channels. Overall, this study enhances knowledge of preferential flow and its role in nutrient and water cycling within natural and agricultural ecosystems. The insights gained from this research can inform the development of improved management strategies for agricultural lands, facilitating sustainable and efficient water resource management.

Keywords: preferential flow; soil heterogeneity; compaction effect; macropores

巴基斯坦谢胡普拉农业区优先流三维结构及其影响因素

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摘要：优先流是水通过土壤中特定路径的运动，而不是通过土壤结构的更均匀的流动。由于土壤的异

质性，例如裂缝、根通道或虫洞，这些优先流动路径经常形成。特别是在土壤深度处，这种分形图案使得理解和描述首选流动路线的行为变得具有挑战性。为了准确地进行地下水和溶质输运建模和预测，需要花费大量时间来理解和描述优先流动路线的增长和演变。在本研究中，使用了各种方法，包括现场观察、土壤样本和成像技术（包括 Origin Lab Pro 和 Sketchup）来检查首选流动的三维结构。我们构建了首选流动路径的三维地图，并使用来自不同农业用地区域的数据检查了它们的分布模式。这项研究是在巴基斯坦谢胡普拉的一个适应性研究农场进行的。在本研究中，结果以 3D 表示形式表示，以便更好地理解优先流。选择了四块 120*120cm 的样地，在四块样地上进行了染料示踪实验，以确认溶质和水的首选流动模式。数据已在 Origin Lab 中进行分析以创建 3D 图形和表格，并使用 Sketchup-2021 Pro 创建 3D 图像。根据本研究发现的水流模式，在没有压实作用的较高位置，首选水流最强，那里大孔隙的连续性得以保留。由于压实作用，微孔隙度降低，且下侧逐渐变弱。结果表明，优先流在压实度最小且大孔隙连续性保持的区域最为突出。相反，压实的影响导致压实区域微孔隙率降低和优先流模式减弱。此外，这项研究揭示了压实和随后的恢复过程如何影响土壤对水流和地表径流的敏感性。通过呈现全面的 3D 表示，这项研究提供了对水流通道的形成和演化的深入理解。总体而言，这项研究增强了对优先流及其在自然和农业生态系统中养分和水循环中的作用的了解。从这项研究中获得的见解可以为制定改进的农业用地管理策略提供信息，促进可持续和高效的水资源管理

关键词: 优先流；土壤异质性；压实效应；大孔隙

1 Introduction

The rapid movement of water through favorable channels in the soil is referred to as preferential flow, bypassing the slower and more diffuse flow through the soil matrix this is known as preferential flow. The intricate network of interconnected macrospores in the three-dimensional structure of preferential flow has a wide range in connection, shape, and size. The profile of the preferred flow is determined by previous soil moisture levels, vegetation, soil properties, land use, and rainfall intensity and duration. The texture, structure, and amount of organic matter significantly affect the preferential flow routes, which in turn affects the size and distribution of macrospores in the soil. By changing the pore structure and soil characteristics, land use activities including tillage, compaction, and the use of fertilizers and pesticides can also have an impact on the structure of the preferred flow. Depending on the type and intensity of the vegetation cover, vegetation can either encourage or obstruct preferred flow. Major elements that affect the beginning and spread of preferential flow channels include rainfall characteristics including intensity, duration, and spatial distribution. The development and existence of preferential flow channels are influenced by the previous soil moisture levels. Understanding the preferred flow's three- dimensional structure and the variables that impact it is necessary for predicting and managing water flow in soil systems. This knowledge is helpful for developing more effective and sustainable agriculture and water management techniques as well as for predicting the fate and transit of pollutants in soil and groundwater systems. Preferential flow is a fundamental phenomenon in soil hydrology that influences how water and solutes move through the soil. In this mechanism, water moves through preferred channels, such as macropores, soil fissures, and root channels, as opposed to the more uniform matrix flow. Predicting pollutant movement in the environment, comprehending the hydrological cycle, and managing soil moisture and nutrients in agricultural systems are just a few of the benefits of understanding preferred flow. For several reasons, research on preferred flow frequently takes place on agricultural land. First, due to changes in soil structure, texture, and organic matter content, agricultural soils are frequently characterized by a high degree of heterogeneity. This may lead to the development of preferred flow routes. For instance, frequent plowing of the soil can produce aggregates of dirt connected by pores, resulting in the construction of continuous channels through which water can flow more preferentially. Like this, the root systems of plants can build pathways for the Movement of nutrients and water, further encouraging preferential flow.

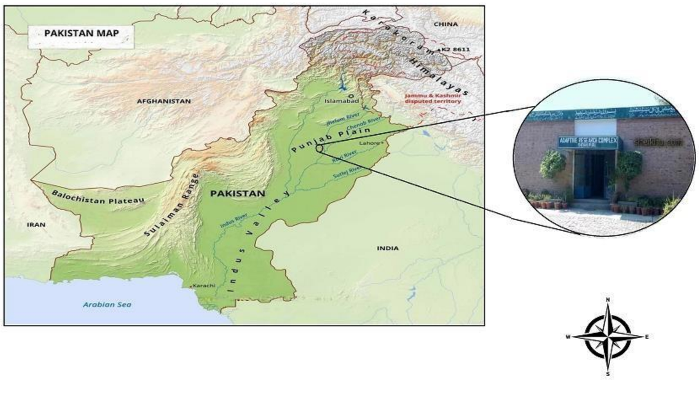
Agricultural land offers a very consistent and accessible surface for gathering data and running preferred flow tests. It is simpler to set up experimental plots and monitor soil water content at various depths and locations in agricultural fields since they are frequently big and flat. Utilizing agricultural land for preference flow studies can also shed light on how agricultural management techniques like tillage, crop residue management, and irrigation can either promote or obstruct preferential flow. The addition of organic matter can improve the production of macropores and boost preferential flow, but tillage can disturb soil aggregates and macropores and hence limit preferential flow. Knowledge gained from research on preferred flow in agricultural land can be used to improve agricultural management procedures like nutrient and irrigation planning. Farmers can optimize irrigation schedules and prevent overwatering, which can result in waterlogging and nutrient leaching, by understanding how water and solutes travel through the soil. Similarly, to this, knowing how nutrients travel through soil can assist farmers in creating specialized nutrient management plans that lower the likelihood of nutrient loss and boost crop output. Pollutants may travel through favored flow pathways from the soil surface to the groundwater like pesticides, fertilizers, and other chemicals, which can contaminate sources of drinking water. Researchers can create models to forecast contaminant transport and create plans to reduce the danger of groundwater pollution by researching preferred flow in agricultural soils.

2 Materials and Methods

2.1 Study Area

To analyze Characteristic behavior and the three-dimensional path of preferential flow, it was decided to conduct our research trials on Adaptive Research Farm Sheikhupura Pakistan. (Located at Sarwar Shaheed Road Civil Lines, Sheikhupura, Punjab, Pakistan).

Fig. 1 Study area (Adaptive Research Farm Sheikhupura, Punjab, Pakistan)



Two compaction trials were conducted to study the three-dimensional dynamics of soil solute transport and water flow. Then we analyzed all the pictures using Origin Lab, Sketchup 2021, and Image-Pro Plus 6.0 and established a three-dimensional model of the water and solute flow in the soil. The compaction trials were conducted on well-structured clay soil (45-54 percent clay) at the Adaptive Research Farm Sheikhupura, Punjab, Pakistan (Upper and Lower, roughly 500 m apart).

2.2 Experimental design

The approach that is most usually used to describe how preferential flow channels are distributed is three-dimensional image analysis with dye tracers. In this study, this methodology was used. The tracer experiments were conducted in September 2022 on Adaptive Research Farm Sheikhupura. Four Plots (120 cm by 120 cm) having a depth of 30cm: two at the upper side and two at the lower site, were designed to check the soil compaction and three-dimensional Preferential flow pattern of water and solute. The compaction treatment was performed by a Combine Harvester Machine, with a tire pressure of 44 psi and with a total load of 3145 KG tire inflation pressure (tire size: 18.4/15-306 PR). Both locations were moldboard plowed toa depth of roughly 20 cm after compaction. The research area was covered by vegetation, and no crop was standing on it.

The following table lists some of the basic features of the soils at the various sites.

Tab. 1 The physical and chemical properties of the upper and the lower site, which are used in determining PF Pathways

Site	Vegetation	Organic content/%	Soil class	Bulk density/(Mg·m^{-3})	Electrical conductivity/(dS·m^{-1})	pH
Upper site	Shabbat grass *Cynodon dactylon*	1.26	Loam	1.65	> 4	8.5
Lower site	Gajar Booti *Parthenium*	1.17	Clay Loam	1.46	< 4	8.1

2.3 Field test of dye tracing

Each plot's (120 cm * 120 cm) area received an initial rainfall of 50 L of water utilizing a Spray Machine with a flat nozzle for the dye tracing test (The average annual rainfall at this area is 600-700 mm). Following 24 hours, 50 L of Brilliant Blue solution (5 g L-1) were given to each plot. Each plot contained three vertical soil profiles that were each 150 cm deep, and the profile walls underwent extensive knife preparation. After that, all values were logged before the preferred flow was measured using a measuring table. The soil was compacted to prevent dye tracer and steel frame intrusion after spraying. Using a sprayer with nozzles that were operated above the center of the frame, to identify preferential flow routes, brilliant blue FCF (5 g L-1) was progressively sprayed on the soil's surface as a dye tracer. The dye solution was transported to the sprayer by a continuous flow pump. The amount of dye tracer consumption is shown in Table 1. During the spraying experiment, an identical depth of water was sprayed at the earth between two steel frames to prevent the vivid blue solution from penetrating laterally. After 24 hours, when the frames were moved, the soil margins surrounding them were disturbed, making it impossible to study anything but the soil's center.

The main portion of the dye area was divided into two horizontal cross-sections, each measuring 120 cm by 120 cm. A digital camera was used to take vertical photos of each horizontal cross-section. After removing the litter layer, I collected soil samples from the surrounding soil of each plot and evaluated the mass moisture content, bulk density, total porosity, mechanical composition, pH, and other variables.

Fig. 2 Application of Brilliant Blue with hand pump

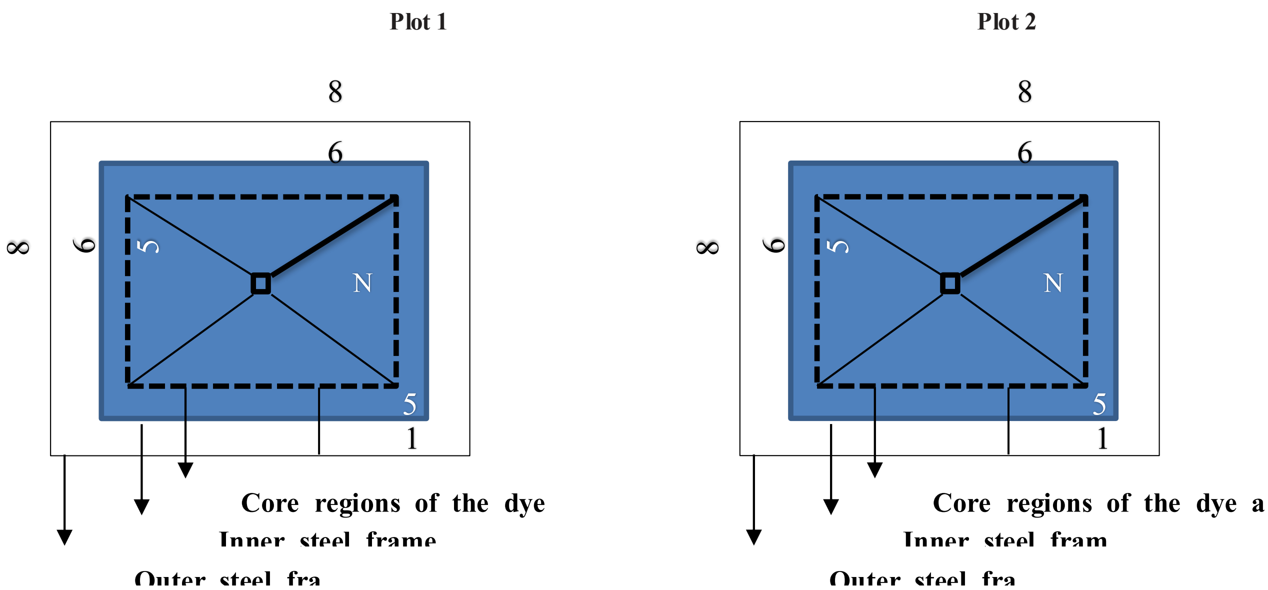
2.4 Soil sample collecting

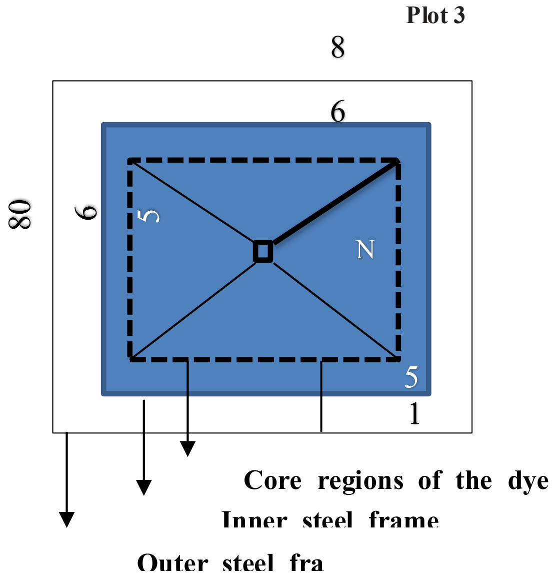
In the compacted and control plots at the Upper and Lower sites, two samples each (20 cm high, 10 cm in diameter) were obtained from the 30–50 cm layer of soil. The soil samples were analyzed after sampling in Soil Testing Laboratory in Sheikhupura Pakistan.

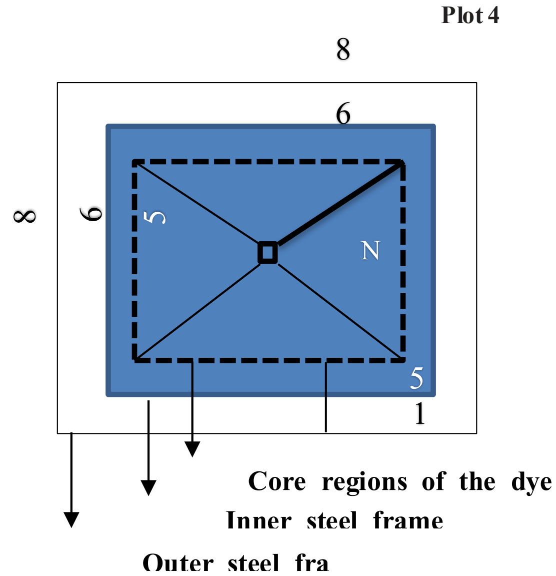
3 Results

By conducting three-dimensional studies, more comprehensive understanding of these key characteristics has been gained. It has become evident that soil water movement is a complex and dynamic process, influenced by factors such as soil properties, the presence of preferential pathways, and the characteristics of the water input.

Fig. 3 Pattern of four plots for dye tracing tests







When Brilliant Blue is applied with water, it enters the soil through various pathways such as leaching or runoff. Once it enters the soil, it mixes with soil water and creates a three-dimensional flow pattern. The movement of Brilliant Blue depends on soil type, texture, structure, and moisture content. For example, it moves more quickly and deeper in sandy soils compared to clay soils. To visualize the three-dimensional flow of Brilliant Blue, techniques such as soil sampling and chemical analysis were used to detect its presence at different depths and locations in the soil.

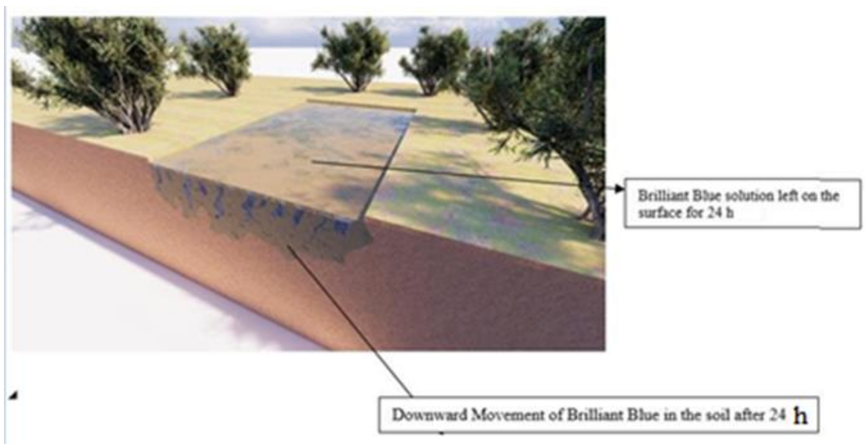
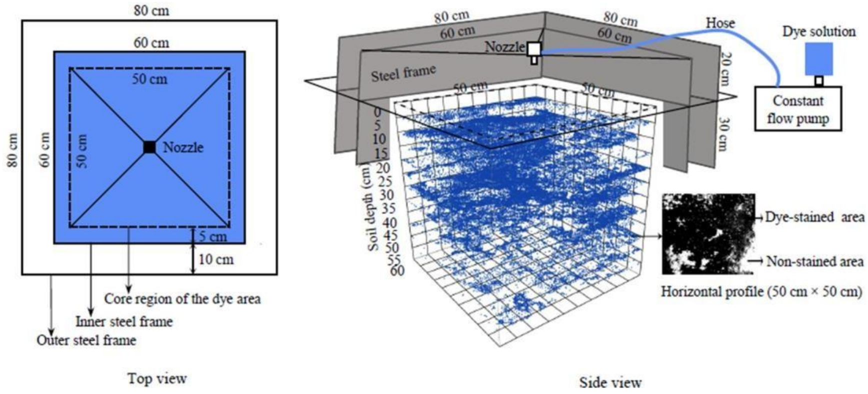


Fig. 4 Downward movement 3D structure of preferential flow inside the soil.

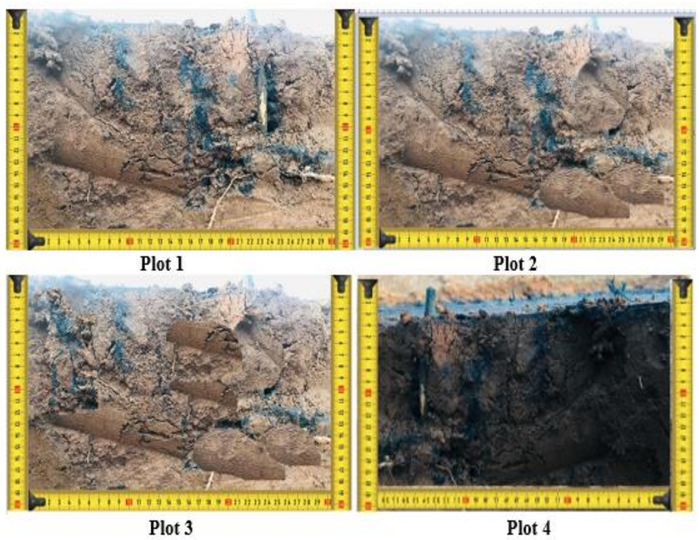
Fig. 4 provide a side view and a downward view, of the preferential flow in a three-dimensional manner. These images were captured using a DSLR camera by adjusting the lens at different positions. The pictures were then processed using SketchUp 2021 and Image-Pro Plus software. Adobe Photoshop CS3 was utilized to adjust the perspective effect of the digital photographs. The dyed areas were colored blue and gray, while the non-dyed sections were painted white. Image analysis was performed using SketchUp 2021, Adobe Photoshop CS3, and Image-Pro Plus 6.0 software. This analysis allowed for the detection and quantification of preferred flow pathways based on the dye-stained portions and unstained areas. Excavation of dye tracing profiles was conducted during the dye tracing tests at the field sites.

Fig. 5 Downward movement 3D structure of preferential flow inside the soil.



Then, dye-tracing images were taken of the plots in bright light. Because of the differences in groundwater levels between the two sites, photos obtained from the soil surface down to 100 cm depth were analyzed at the Upper site, whereas images taken from the soil surface down to just 70 cm depth were analyzed at the Lower site. To analyze the images, software such as SketchUp 2021 and Adobe Photoshop CS3 were used to distinguish dyed areas from non-dyed areas through changes in brightness, contrast, hue, and saturation. The dyed parts were replaced with black and the non-dyed parts with white. The Image-Pro Plus 6.0 software was used to transform the image into numerical matrices and determine the size and spatial location of the preferred flow pathways. The software's classification and count features aided in distinguishing the different size classes and spatial locations of the preferred flow. The data obtained included the coordinates and radius of the dyed regions. Additionally, image rectification and statistical methods were employed to detect the locations of plant roots in the horizontal images. The stained area served as the basis for computing the radius of influence, and the area of each colored zone was equal to the number of pixels each plaque occupied, which were approximately represented as rings. Then, a data file containing the coordinates at the center point and radius of the dyed regions was produced. After initial image rectification, an artificial statistical method was used to detect the locations of the plant roots in the horizontal images.

Fig. 6 Pattern of preferential flow of water in 04 plots after 24 h



The above pictures show the real-time movement of Brilliant Blue in the soil, this image demonstrates that Brilliant Blue reaches a maximum depth of 15.5 cm in the soil. The Movement of FCP depends on different factors like roots, pores, cracks, etc. The brilliant blue goes maximum depth where the roots were available. In this study, I have tried to show brilliant blue Movement in three-dimensional way by using Sketch Pro software for a better understanding of it. I measured the depth of Movement with the help of a steel frame.

Tab. 2 Soil parameters of four plots

Parameter	Plot 1	Plot 2	Plot 3	Plot 4
Porosity/%	8%	8%	7.90%	7.93%
Large macropores>1.2 mm	0.46%	0.35%	0.16%	0.09%
Small macropores>0.3 mm	4.00%	2.00%	0.1%	0.00%
No. of pores >1.2mm	642.30	652.10	448.60	302.80
Length of infiltration	25cm	29cm	35cm	39cm
Bulk density (g cm^{-3})	1.31 g cm^{-3}	1.38 g cm^{-3}	1.37 g cm^{-3}	1.46 g cm^{-3}
Saturated hydraulic conductivity (Ks) (cm h^{-1})	37.70 cm h^{-1}	32.00 cm h^{-1}	10.09 cm h^{-1}	0.09 cm h^{-1}
Air Permeability (μm^2)	33.50 μm^2	21.00 μm^2	12.10 μm^2	4.00 μm^2

4 Conclusion

This study reveals that preferential flow can lead to the formation of distinct channels or flow paths within the soil. By conducting three-dimensional studies, we gained a more comprehensive understanding of the preferential flow patterns. Visualization of the movement of water and dye in the soil using techniques such as soil sampling, chemical analysis, and image analysis software has been done. The images and data obtained allowed for the detection and quantification of preferential flow pathways based on the dye-stained portions and unstained areas. This study also investigated the quantities and locations of preferential flow paths under various infiltration conditions. It was found that the amount of infiltration directly influenced the depth of dye infiltration and the number of preferential flow pathways. As the infiltration rates increased, the staining depth and the number of preferential flow paths also increased. The analysis revealed different distribution patterns of preferential flow channels at various soil depths and infiltration intensities. It was observed that at smaller scales and shallower soil depths, preferential flow tends to be more localized and uneven. As the scale increases and soil depth deepens, preferential flow becomes more organized and structured, guided by larger soil structures. The impact of compaction on soil pore structure and transport characteristics. Compaction resulted in a decrease in the percentage of large mesopores and had a negative effect on soil hydraulic conductivity and air permeability. This research provides valuable insights into the key characteristics, three-dimensional flow patterns, spatial distribution, and the impact of compaction on preferential flow in soil water movement. These findings contribute to a better understanding of soil hydrology and its implications for water movement in agricultural systems.

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