



Influence of Agroforestry Practices, Sampling Depth, and Canopy Cover on Soil Physicochemical Properties in Waterlogged Areas of Faisalabad

Amjad Saeed^{1*}, Ahtesham ul Hassan¹ and Imran Khalid²

¹Institute of Forest Sciences, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, 63100, Punjab, Pakistan

²Department of Agriculture Extension, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, 63100 Punjab, Pakistan

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Abstract

Waterlogging significantly alters soil physical and chemical properties, reducing soil health and productivity in affected regions. This study evaluated the role of agroforestry practices in improving soil conditions across three waterlogged sites in District Faisalabad (Chak Jhumra, Sitana, and Sangla Hill). Soil samples were collected at two depths (0-15 cm and 15-30 cm) under two canopy positions (under canopy and away from canopy) to assess variations in soil pH, EC, organic matter, bulk density, saturation percentage, and macronutrient contents (N, P, K). Results showed significant differences among sites, depths, and canopy positions. Chak Jhumra consistently exhibited the highest soil pH, EC, nutrient availability, and organic matter, while Sangla Hill showed the lowest values across most parameters. Surface soils (0-15 cm) generally contained higher nutrient concentrations and organic matter but lower bulk density compared to deeper layers. Canopy presence markedly improved soil quality, with higher N, P, K contents and organic matter recorded under canopy compared to away from canopy. These improvements are attributed to litter deposition, moderated soil microclimate, and reduced erosion. The findings demonstrate that agroforestry practices positively influence soil fertility and structure in waterlogged environments and highlight the importance of canopy management and depth-specific assessment for soil reclamation strategies.

1. Introduction

Waterlogging is a pervasive soil constraint in irrigated and semi-arid regions, causing significant modifications in soil physicochemical properties that ultimately impair crop productivity and ecosystem functioning. When soil becomes saturated, oxygen diffusion declines drastically, nearly

10,000 times slower in water than in air, leading to hypoxic or anaerobic conditions that inhibit root respiration, nutrient uptake, and soil microbial activity (Trought & Drew, 1980a; Drew & Lynch, 1980). These changes often result in increased soil compaction, reduced structural stability, nutrient imbalances, and the accumulation of phytotoxic compounds, especially in fine-textured soils with poor

drainage (Hodgeson, 1982; Barrett-Lennard, 2002). In Pakistan, nearly 6.17 Mha of land is affected by waterlogging, with 1.16 Mha simultaneously exposed to salinity, posing serious challenges to agricultural sustainability (Rafiq, 1990; Qureshi, 1986).

Agroforestry offers a promising biological strategy to rehabilitate degraded and waterlogged soils by integrating deep-rooted perennial trees into agricultural landscapes. Trees improve soil physical structure through enhanced root penetration, increased porosity, and improved drainage, while also contributing organic matter through litter fall and root turnover (Pandey 2002; Akinbile et al., 2007). Canopy cover additionally modifies the soil microenvironment by lowering temperature fluctuations, reducing erosion, and promoting nutrient cycling, which collectively enhance soil fertility and resilience in stressed environments (Battaglia et al., 2000; Bullock et al., 2011). These interactions differ between surface and subsurface layers, as topsoil typically accumulates more organic matter and nutrients, whereas deeper layers often show higher bulk density and reduced aeration.

The effectiveness of agroforestry in improving soil quality, however, varies with species composition, canopy distribution, and local hydrological conditions. In waterlogged landscapes, tree species with adaptive traits, such as efficient gas exchange mechanisms, adventitious roots, or high organic matter inputs, can substantially improve soil structure and nutrient availability compared to areas without canopy influence (Kozlowski 1997; Parolin & Wittmann 2010). Despite this potential, limited information exists on how agroforestry practices interact with sampling depth and canopy position to influence soil properties in waterlogged environments of semi-arid Pakistan.

Therefore, the present study aims to evaluate the influence of agroforestry practices on key soil physicochemical attributes, pH, EC, organic matter, bulk density, saturation percentage, and macronutrients (N, P, K), across different soil depths and canopy positions in waterlogged areas of Faisalabad. Understanding these spatial and management-induced variations is essential for designing sustainable soil reclamation strategies in regions vulnerable to chronic waterlogging.

2. Materials and Methods

2.1 Description of Study Sites

The study was carried out under semi-arid environmental conditions in two districts of Punjab, Pakistan, Faisalabad and Nankana Sahib, to evaluate the impact of waterlogging on the growth of selected agroforestry tree species. Three sites (Satyana, Chak Jhumra, and Sangla Hill) were randomly selected for farmer interviews and soil sampling. Field surveys were conducted from February 2017 to September 2018. A total of 450 farmers (150 per site) were interviewed, and 120 soil samples were collected, 40 from each site at two soil depths.

A. Faisalabad

Faisalabad, often referred to as the “Manchester of Pakistan,” is the third most populous city in the country and the second largest in Punjab. It is one of the earliest planned cities of British India and serves as a major hub for the textile industry. The district produces various crops and fruits, including wheat, sugarcane, rice, maize, citrus, guava, and mango, along with a wide range of vegetables.

Faisalabad covers an area of 5,856 km² and is located at 31°25'7.37"N latitude and 73°4'44.79"E longitude, at an elevation of 184 meters above sea level. The summer season extends from April to October, with May to July being the hottest months, while winter lasts from November to March, with December to February being the coldest period. The district has an average annual temperature of 24.2 °C and an average rainfall of 346 mm (Fig. 1). Administratively, it consists of six tehsils and 189 union councils. From this district, 300 farmers were interviewed, and 80 soil samples were collected across two sites.

Study Sites within Faisalabad District

1. **Satyana**
2. **Chak Jhumra**

B. Nankana Sahib

Nankana Sahib is a city and the administrative capital of Nankana Sahib District in the Punjab province of Pakistan. It is named after Guru Nanak, the first Guru of the Sikhs, who was born here and began his early preaching in this area. Today, the city holds great historical and religious significance and is an important pilgrimage destination for Sikhs from around the world. Nankana Sahib is located approximately 75 km west of Lahore and 55 km east of Faisalabad. Until 2005, it was part of Sheikhupura District.

The present Nankana Sahib District consists of three tehsils: Nankana Sahib, Shah Kot, and Sangla Hill. The region has a desert-type climate. June is the hottest month, with an average temperature of around 34.0 °C, while January is the coldest month, with an average temperature of 12.1 °C. The annual variation in temperature is about 21.9 °C, and the difference in precipitation between the driest and wettest months is approximately 99 mm.

Site of District Nankana Sahib

1. Sangla Hill

2.2 Collection of Soil Samples

Soil samples were collected at 2 depths (0-15 cm), (15-30cm) from 3 sites of two selected with the help of soil auger. A total number of 120 samples, 40 for each depth were collected from the fields where farmers were already practicing agroforestry for the reclamation of waterlogging. Soil sampling was done under and away from canopy of the available agroforestry tree species.

2.3 Sample Preparation for Soil Analysis

2.3.1 Soil filtrate preparation by mechanical shaker

The 20 g of grinded soil was taken in a stoppered flask; half of it filled with double distilled water, allowed to shake for 30 minutes at mechanical shaker and kept it overnight. Next day it was filtered and volume was made up to 100 ml with double distilled water. The filtrate was used for the determination of pH, electrical conductivity, carbonate, bicarbonate, calcium, magnesium, chloride, sodium, potassium, phosphorus and sulphur contents.

2.3.2 Digestion of soil sample

For the estimation of nitrogen, digestion of soil samples was carried out. 3 g of finely grinded soil sample was taken in digestion flask, one g catalyst mixture and 25 ml of conc. H₂SO₄ were added and heated for 5-6 hours. Finally, light green colored solution was remained in flask. Volume was made upto 100 ml by double distilled water. Positive and negative controls were also prepared to find out error. In case of positive control 3 g urea was taken instead of sample and whole process was repeated, and in case of negative control whole process was carried out in presence 1 g catalyst and 25 ml of H₂SO₄.

Various experimental techniques used for the estimation of

different contents in plants and soil samples are listed below.

2.4 Measurement of pH

The pH meter was calibrated by using buffer solutions having pH value 4 and 7. Then, pH of sample solutions was measured by dipping the glass-calomel electrode of pH meter in the sample solutions one by one (Sumner, 1994).

2.5 Measurement of Electrical Conductivity

The conductivity meter was calibrated with a standard KCl solution at 25° C. Then conductivity of sample solutions was measured by dipping the electrode in the sample solutions. The observed EC was measured in dS m⁻¹ (Gupta et al., 2012).

2.6 Soil NPK Analysis

Soil samples are collected from the field, air-dried, ground, and sieved through a 2-mm mesh before analysis. Available nitrogen (N) is determined using the alkaline potassium permanganate method, where soil is digested with KMnO₄ and the released ammonia is distilled and measured (Manna et al., 2021). Available phosphorus (P) is extracted using the Olsen sodium bicarbonate method and quantified colorimetrically using a spectrophotometer (Sharma et al., 2022; Zhang et al., 2021). Exchangeable potassium (K) is extracted with 1N ammonium acetate and quantified using a flame photometer, which provides accurate estimates of plant-available K under diverse soil conditions (Kumar et al., 2023). These standardized methods allow rapid and reliable estimation of soil NPK status required for nutrient management in agroecosystems.

2.7 Bulk Density

Surface debris and the O horizon were removed before sampling. For subsurface horizons, a pit was dug to the desired depth, and a flat area slightly larger than the metal cylinder was prepared. The cylinder (50-75 mm height) was driven into the soil with a hammer until level with the surface, then carefully excavated, removed, and trimmed flush at both ends. Any small holes were filled; samples with large holes were discarded. The sample was placed in a labeled plastic bag. In the laboratory, samples were oven-dried at 104 °C for 24 hours to obtain dry weight. Bulk density was then calculated as:

$$BD \text{ (g/cm}^3\text{)} = W / V,$$

where W is the oven-dry weight (g) and V is the cylinder volume (cm^3).

2.8 Statistical Analysis

Data was analyzed using the statistical package SPSS version 11.0. ANOVA was performed as described by Steel and Torrie (1981). A R-value of <0.05 was considered significantly different. All data presented were expressed as mean $\pm$ standard error.

3. Results

3.1 Soil pH

Results for soil pH of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 1). All the sampling sites were statistically significant with each other regarding soil pH. Soil pH of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 7.18 to 7.86. According to current observation, maximum soil pH (7.86) was observed in the Chak Jhumra when soil samples were taken from 0-15 cm depth and away from the canopy followed by in same place at same sampling depth but under the canopy of trees. While minimum soil pH (7.18) was observed in the Sangla Hill when soil samples were taken from 15-30 cm depth and under the canopy. The order of sampling points for the soil pH was Chak Jhumra $>$ Satyana $>$ Sangla Hill, while for sampling depths 0-15 cm $>$ 15-30 cm and agro forestry techniques was away canopy $>$ under canopy.

3.2 Soil EC

In current study, results for soil EC of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 2). All the sampling sites were statistically significant with each other regarding soil EC. Soil EC of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 1.22 to 1.58. According to current observation, maximum soil pH (1.58 dsm^{-1}) was observed in the Chak Jhumra when soil samples were taken from 15-30 cm depth and under canopy followed by in same place under canopy but sampling depth was 0-15 cm. While minimum soil EC (1.22 dsm^{-1}) was observed in the Sitana when soil samples were taken from 0-

15 cm depth and sampling collection was done away from canopy. The order of sampling points for the soil EC was Chak Jhumra $>$ Sangla Hill $>$ Satyana, while for sampling depths 0-15 cm $>$ 15-30 cm and agro forestry techniques was under canopy $>$ away canopy.

Figure 1: Effect of various agroforestry practices on the soil pH at various depths in selected areas of Faisalabad

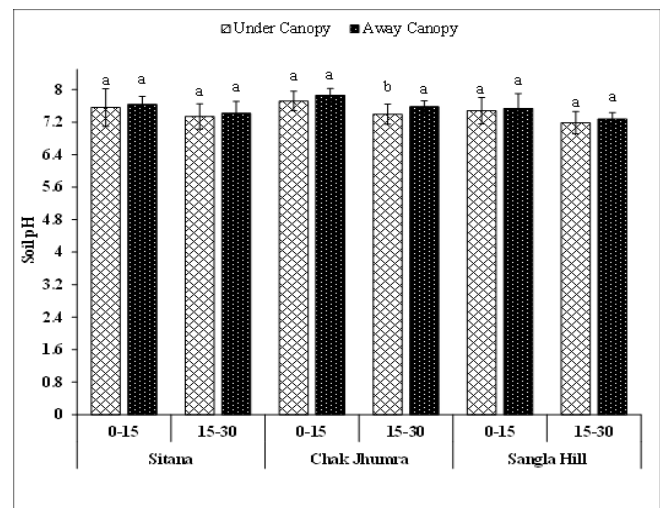
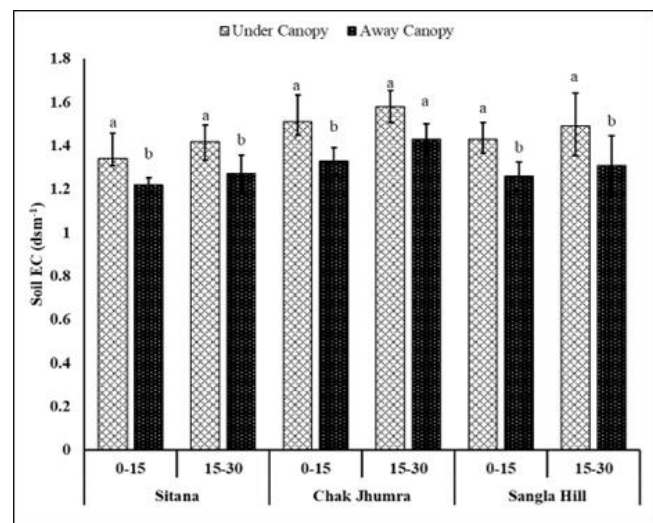


Figure 2: Effect of various agroforestry practices on the soil EC (dsm^{-1}) at various depths in selected areas of Faisalabad



3.3 Soil Potassium Contents (mg kg^{-1})

Findings of current study revealed that soil potassium

contents of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 3). All the sampling sites were statistically significant with each other regarding soil potassium contents. Soil potassium contents of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 117.4 – 151 mg kg⁻¹. According to current observation, maximum soil potassium contents (151 mg kg⁻¹) was observed in the Chak Jhumra when soil samples were taken from 0-15 cm depth and under canopy followed by in the soil samples of Sitana under canopy but sampling depth was 0-15 cm. While minimum soil potassium contents (117.4 mg kg⁻¹) was observed in the Sangla Hill when soil samples were taken from 15-30 cm depth and sampling collection was done away from canopy. The order of sampling points for the soil potassium contents was Chak Jhumra > Sitana > Sangla Hill, while for sampling depths 0-15 cm > 15-30 cm and agro forestry techniques was under canopy > away canopy.

3.4 Soil Nitrogen Contents (%)

Current study revealed that soil nitrogen contents of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 4). All the sampling sites were statistically significant with each other regarding soil nitrogen contents. Soil nitrogen contents of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 0.023 – 0.051%. According to current observation, maximum soil nitrogen contents (0.051%) was observed in the Chak Jhumra when soil samples were taken from 0-15 cm depth and under canopy followed by in the soil samples of same area away from canopy but sampling depth was 0-15 cm. While minimum soil nitrogen contents (0.023%) was observed in the Sitana when soil samples were taken from 15-30 cm depth and sampling collection was done away from canopy. The order of sampling points for the soil nitrogen contents was Chak Jhumra > Sangla Hill > Sitana, while for sampling depths 0-15 cm > 15-30 cm and agro forestry techniques was under canopy > away canopy.

Figure 3: Effect of various agroforestry practices on the soil potassium contents (mg kg⁻¹) at various depths in selected areas of Faisalabad

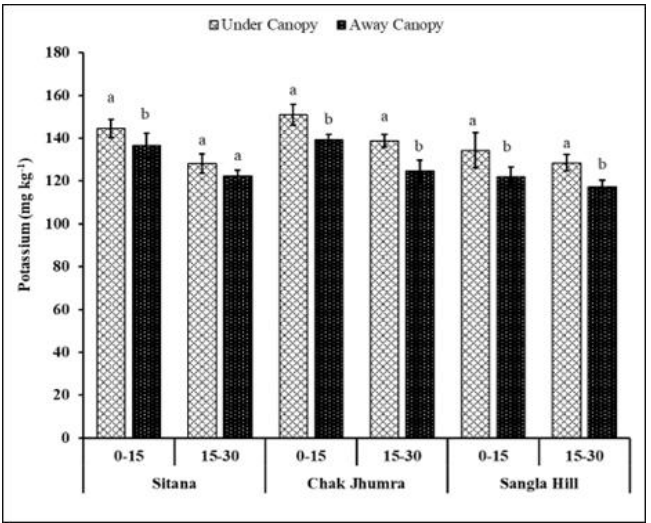
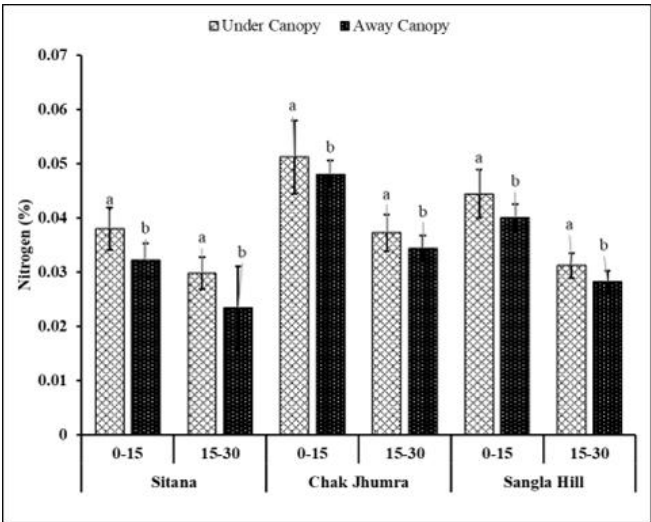


Figure 4: Effect of various agroforestry practices on the soil nitrogen contents (%) at various depths in selected areas of Faisalabad



3.5 Soil Phosphorous Contents (mg kg⁻¹)

Findings of current study revealed that soil phosphorous contents of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 5). All

the sampling sites were statistically significant with each other regarding soil phosphorous contents. Soil phosphorous contents of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 4.80 – 6.84 mg kg⁻¹. According to current observation, maximum soil phosphorous contents (6.84 mg kg⁻¹) was observed in the Chak Jhumra when soil samples were taken from under canopy at 0-15 cm depth followed by in the soil samples of same area under the canopy but sampling depth was 15-30 cm. While minimum soil phosphorous contents (4.80 mg kg⁻¹) was observed in the Sangla Hill when soil samples were taken from away from the canopy at the 15-30 cm depth. The order of sampling points for the soil phosphorous contents was Chak Jhumra > Sitana > Sangla Hill, while for sampling depths 0-15 cm > 15-30 cm and agro forestry techniques was under canopy > away canopy.

3.6 Soil Organic Matter (%)

Results revealed that soil organic matter of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 6). All the sampling sites were statistically significant with each other regarding soil OM contents. Soil OM contents of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 0.53 – 0.85%. According to current observation, maximum soil OM contents (0.85%) was observed in the Chak Jhumra when soil samples were taken from under canopy at 0-15 cm depth followed by in the soil samples of same area away from canopy but sampling depth was 15-30 cm. While minimum soil OM contents (0.53%) was observed in the Sangla Hill when soil samples were taken from away from the canopy at the 15-30 cm depth. The order of sampling points for the soil phosphorous contents was Chak Jhumra > Sitana > Sangla Hill, while for sampling depths 0-15 cm > 15-30 cm and agro forestry techniques was under canopy > away canopy.

3.7 Saturation Percentage (%)

Results of current study revealed that saturation percentage of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 7).

Figure 5: Effect of various agroforestry practices on the soil phosphorus contents (mg kg⁻¹) at various depths in selected areas of Faisalabad

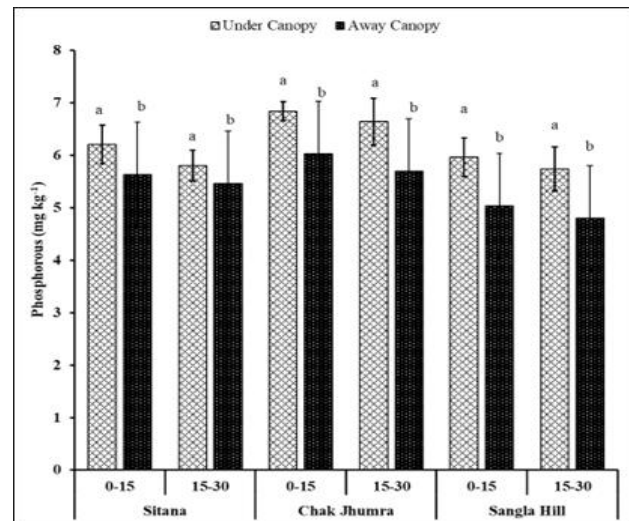
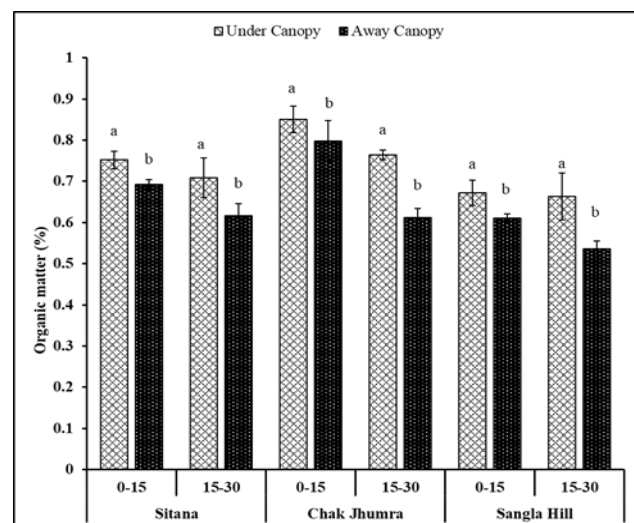


Figure 6: Effect of various agroforestry practices on the soil organic matter (%) at various depths in selected areas of Faisalabad



All the sampling sites were statistically significant with each other regarding saturation percentage of soil. Saturation percentage of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 31.00 – 47.50%. According to current observation,

maximum saturation percentage (47.50%) was observed in the Chak Jhumra when soil samples were taken from under canopy at 15-30 cm depth followed by in the soil samples of same area under the canopy but sampling depth was 0-15 cm. While minimum saturation percentage of soil samples (31.00%) was observed in the Sangla Hill when soil samples were taken from away from the canopy at the 0-15 cm depth. The order of sampling points for the soil saturation percentage was Chak Jhumra > Sitana > Sangla Hill, while for sampling depths 15-30 cm > 0-15 cm and agro forestry techniques was under canopy > away canopy.

3.8 Soil Bulk Density (g/cm³)

Findings of current study revealed that soil bulk density of various samples collected from different waterlogged areas of District Faisalabad at various sampling depth using various practices (under the canopy and away from the canopy) showed significant variation (Figure 8). All the sampling sites were statistically significant with each other regarding soil bulk density. Soil bulk density of all the sampling sites showed variation regarding the sampling depth and observed to be in range from 1.21 – 1.37 g/cm³. According to current observation, maximum soil bulk density (1.38 g/cm³) was observed in the Chak Jhumra when soil samples were taken away from canopy at 0-15 cm depth followed by in the soil samples of same area away from canopy but sampling depth was 15-30 cm which were also statistically at par with each other. While minimum soil bulk density soil samples (1.21 g/cm³) was observed in the Sangla Hill when soil samples were taken from under the canopy at the 0-15 cm depth. The order of sampling points for the soil bulk density was Chak Jhumra > Sitana > Sangla Hill, while for sampling depths 15-30 cm > 0-15 cm and agro forestry techniques was away from canopy > under the canopy.

3.Discussion

Soil flooding induces composite and dynamic pressure in plants known as either submergence or water logging stress depending on the depth of the water table. Throughout nature, these stresses determine the composition of the ecosystem's organisms. It causes economic harm to agricultural land as well as soil health issues, which have long-term social consequences (Whitmore and Whalley, 2009). Water logging condition is commonly described when saturated soil and/or water pounded on the surface of the soil are evident.

Figure 7: Effect of various agroforestry practices on the saturation percentage (%) at various depths in selected areas of Faisalabad

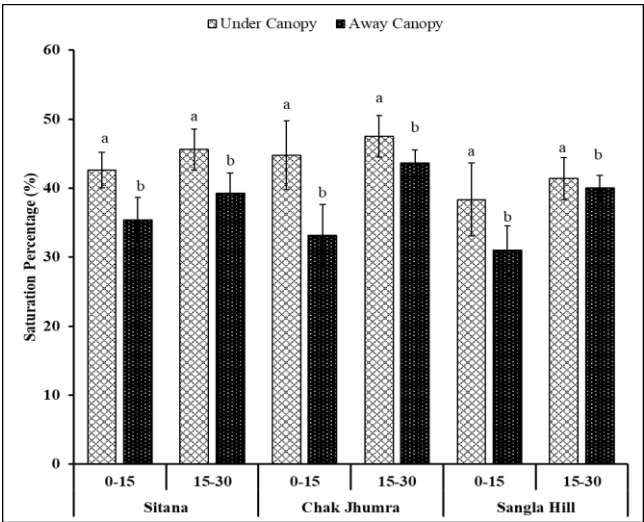
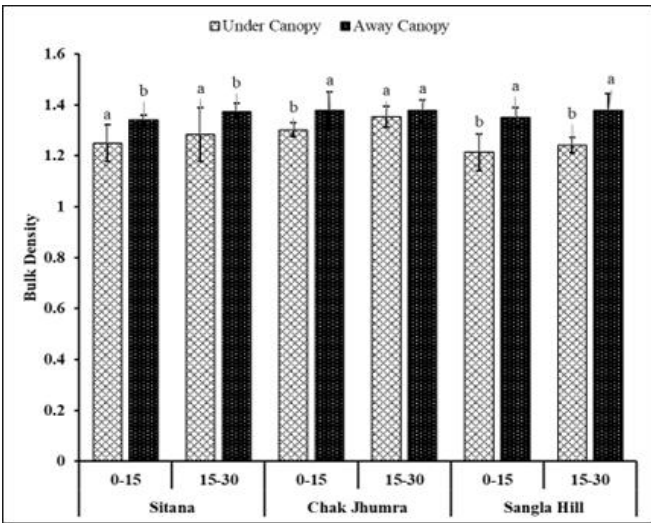


Figure 8: Effect of various agroforestry practices on the soil bulk density (g/cm³) at various depths in selected areas of Faisalabad



Water logging will occur either where the water table is rising or if the water is continually applied to the surface, e.g. during irrigation or high-intensity precipitation where the soil has slow drainage (Visser and Voesenek 2005). Reductions in

crop growth and excess water yield in soil can be largely attributed to three major influences I the direct effect of low oxygen concentrations in soil around roots (rhizosphere) on plant physiological processes; (ii) Changes in soil chemistry and decreased availability of nutrients resulting in toxicity of some elements and shortages of others; and (iii) changes in microbial activity affecting normal rhizosphere processes (McFarlane *et al.*, 2003).

Current study revealed that selected areas are more prone to water logging stress. All the water logged areas showed that water logging stress significantly affected the soil health. It is clear from the current findings that depth of sampling also affects the soil related attributes of all the areas; however, canopy cover also showed variation in the soil related attributes and nutritional status of the soil.

Water logging leads to a loss of oxygen in the soil because the floodwater entering the soil removes oxygen-rich air from the soil pores. In contrast, 10 000 times the higher diffusion resistance of oxygen in water than in air contributes to an obstruction of soil oxygen supply in water-saturated soils (Aroca *et al.*, 2011)). Microbial and plant activities rapidly absorb the remaining oxygen, resulting either in hypoxic (low-oxygen concentrations: mitochondrial respiration reduced; fermentation occurs) or anoxic (oxygen absent: energy gain by fermentation only) conditions (Bailey-Serres and Voesenek, 2008). Due to lack of oxygen, soil physicochemical properties, such as pH and redox potential, strongly vary during water logging (Pezeshki *et al.*, 1996). Decreased gas diffusion velocity between soil and atmosphere causes an accumulation of gaseous compounds in waterlogged soils such as plant hormone ethylene or other metabolic products such as carbon dioxide (Jackson and Colmer, 2005). Oxygen deficiencies also affect soil microbial communities (Unger *et al.*, 2009) and various microbial processes, which ultimately lead to changes in soil chemical composition. This can lead to a reduced abundance of oxidized nutrients (e.g. NO_3^- , SO_4^{2-} , Fe^{3+}) and increased levels of reduced compounds, such as Mn^{2+} , Fe^{2+} , H_2S , NH_4^+ and organic compounds (alkanes, acids, carbonyls, etc.), which may be toxic to plants (Lucassen *et al.*, 2002; Jackson and Colmer, 2005). The velocity and extent of changes in soil physicochemical properties depends on the type of soil, the duration of the water logging event, the prevailing environmental conditions (such as temperature) and the type of flood or water logging. Stagnating conditions reduce the

availability of oxygen in the soil much faster, leading to more stressful conditions than moving floodwaters where turbulence occurs. facilitate oxygen solubilization in the floodwater (Hüve *et al.*, 2007).

Results revealed that depth of sampling also affects the soil nutrient of all the areas. Several physical, chemical and biological processes change during flooding, which may alter soil capacity to support plant growth (Thomas and Hilker, 2000). In many cases, soil micro-organisms use oxygen as the terminal electron acceptor for the degradation of organic compounds. In the event of flooding, nitrate replaces oxygen as the terminal electron receptor in microbial respiration leading to denitrification and/or nitrate ammonification (Cai, 2002). In addition, three nitrate-reducing pathways are known in soils: (1) dissimilar nitrate reduction to ammonia (DNRA or accumulators), (2) dissimilar nitrogen bacteria that can only reduce nitrate to nitrite (accumulators), (2) nitrogen dissimilating bacteria which are only capable of reducing nitrate to nitrite (accumulators) and (3) denitrifiers which are capable of reducing nitrate to nitrous oxide or dinitrogen (Nijburg and Laanbroek, 1997; Cai, 2002). Bacterial nitrate degradation is known to be a significant loss of available soil nitrogen (Martínez-Alcántara *et al.*, 2012). This cycle causes competition between the root and the bacteria for nitrate. Floods also affect the absorption of nutrients by plants (García-Cebrián *et al.*, 2003). Soil logging decreases nutrient levels in the soil and ultimately results in nutrient deficiency in the main plant (Steffens *et al.*, 2005). Likewise, nutrient concentrations are decreased when plants are grown in N_2 -flushed or stagnant nutrient solutions (Wiengweera and Greenway 2004); these findings from nutrient solutions promote root hypoxia, which prevents breathing, to minimize root nutrient uptake and/or xylene transport. In contrast, water logging frequently changes soil nutrient dynamics. Phosphorous supply can increase as Fe solubilizes (Elzenga and van Veen, 2010). Nitrate loss-related denitrification can occur in waterlogged soils, including soils (Hüve *et al.*, 2007; Hamonts *et al.*, 2013).

Results revealed that depth of sampling also affects the soil nutrient of all the areas; however, canopy cover also showed variation in the soil nutritional status of the soil. Findings from the current study found that the cover of the canopy showed variability in soil nutritional status. Waring *et al.* (2015) reported that plants would have a greater effect on soil chemistry in patchy landscapes than in ecosystems with

continuous plant cover because the effects on individual trees are smaller for closed canopies (Powers *et al.*, 2004). Soil nutrient content is higher under vegetation in wooded areas where canopy coverage is usually low, between 20% and 30% (Bonanomi *et al.*, 2008). Rodríguez *et al.* (2011) reported that soil spatial variability was 17-fold higher among isolated individuals than within the forest. Wei *et al.* (2010) have shown that soil OC and TN concentrations and stocks in the top 10 cm layer are almost twice as high under the outer canopies of different tree species. The OC (6.31 per cent) and TN (14.86 per cent) differences between under and outside canopies at our study site were much smaller.

Not only is herbaceous vegetation an important source of organic matter, it can also reduce soil erosion. Field *et al.* (2012) reported that self-reinforcing "fertile island" was due to the transfer of material from increased erosion of bare patches to shrub patches when grass cover was reduced. Previous studies showing higher soil nutrient content in vegetation have reported more herbaceous biomass below than outside canopies (Cao *et al.*, 2016). Flowering herbaceous vegetation preferred nutrient status in areas between trees and shrubs, which may partly account for significant differences in nutrient content within and outside the canopies.

Our study reported four major findings about differences in soil nutrient contents under and outside tree and shrub canopies associated with plant species, slope section, and soil depth in a water logged areas of Faisalabad. All the soil attributes, differed significantly among sampling areas, sampling depth and canopy positions. These results can help to optimize sampling strategies in water logged land areas around the world. Studies that systematically analyze the effect of canopy coverage on differences in soil properties under and outside canopies are needed.

Conclusion

This study demonstrates that agroforestry practices play a significant role in improving soil physicochemical properties in waterlogged areas of Faisalabad. Soil quality varied markedly across sites, depths, and canopy positions, with Chak Jhumra showing comparatively better soil fertility and organic matter status than Sitana and Sangla Hill. Surface soils (0–15 cm) consistently exhibited higher nutrient concentrations, greater organic matter, and lower bulk density, highlighting their greater responsiveness to

management interventions. Canopy cover proved particularly beneficial, as soils under tree canopies showed enhanced N, P, and K levels, increased organic matter, and improved structural attributes compared to areas away from the canopy. These improvements are linked to organic litter inputs, microclimate regulation, and reduced erosion. Overall, the findings confirm that well-managed agroforestry systems can effectively mitigate the adverse impacts of waterlogging by enhancing soil fertility and physical structure. Incorporating canopy-based strategies and depth-specific soil monitoring can support sustainable land management and reclamation efforts in waterlogged agroecosystems.

Authorship contribution statement

Amjad Saeed: Conceptualization, Investigation, Formal analysis, Writing original draft. Data curation, Methodology; Umer Saleem: Formal analysis and data curation. Ahtesham ul Hassan and Imran Khalid: Data curation, Formal analysis, and writing the review.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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