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A Study on the Relationship Between Wheat Root Development and Soil Texture

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ABSTRACT

The wheat root system is crucial for nutrient uptake, drought tolerance, and crop yield. This study explores the impact of soil texture on wheat root development, focusing on sandy, loamy, and clayey soils in two wheat varieties, Saraybosna and Alparslan. Using PVC tubes filled with different soils, root traits such as length, depth, diameter, volume, and dry weight were analyzed with image analysis software. Results showed that soil texture significantly affects root growth, with sandy and loamy soils promoting better development than clayey soil. Saraybosna exhibited superior root growth across all soil types, especially in sandy soil, achieving the highest root length and dry weight. In contrast, Alparslan showed reduced growth in clayey soil. Principal Component Analysis (PCA) identified root dry weight, depth, and length as key factors influencing development. These findings emphasize the importance of soil texture in root growth and optimizing wheat variety selection for better yields. The results also highlight the importance of root system plasticity, which is a still not well-known trait.

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Introduction

important and urgent (Maqbool et al., 2022). As a crucial organ, the root system is often the first to perceive environmental changes and stress. Therefore, a healthy and developed root system can ensure the good development of the plant shoot system and is essential to guarantee the later yield of crop production (Freschet et al., 2021).

Wheat is an important cereal crop that meets the basic needs of more than one-fifth of the people around the world. Its root system plays an essential function in nutrient absorption and drought tolerance during the wheat-growing season (Kou et al., 2022). Roots are the main organs in contact with the soil and have a direct impact on the morphology, development, and yield of crop. Plants may absorb more water and nutrients from the soil as their root length and surface area increase, which is important at all stages of crop growth (Chen et al., 2022). The ability of roots to take up nutrients directly effects wheat plant density, multiplication, seeding, and spike development, additionally, they determine the amount of chlorophyll present in leaves, the chlorophyll index, and the wheat yield (Guo, et al., 2019).

Root development is significantly affected by both genetic factors and environmental conditions, particularly soil and rhizosphere properties (Wendel et al., 2022; George et al., 2024). Various processes that were considered to derive only from environmental influences such as changes in soil texture, nutrient availability, and pH levels—actually exhibit a complex relationship between these soil features and intrinsic genetic traits. Understanding this relationship is crucial for optimizing root growth and, consequently, overall plant health. (Balliu et al., 2021; Gusain et al., 2024). For most plants, differing soil environments may result in visible differences in root distribution density, root system type, and root development ratio. Root system architecture (RSA) is a complex, quantitatively inherited trait that is directly related to plant growth environment as well as crop yield and quality. Soil fertility, soil structure, and soil moisture are some of the key physical and chemical factors that

influence root distribution, development, and absorption. In recent years, soil-root interactions in agriculture and plant physiology have received increased attention, with developing insights into their underlying linkages. (Ogilvie et al., 2021; Hudek et al., 2022). These interactions play a crucial role in plant survival, enhancing both crop yield and soil quality.

Soil texture refers to the specific composition and relative size of individual soil particles at a fundamental scale, and it is commonly classified based on the proportion of sand, silt, and clay particles present among the total soil particles that make up a given soil sample. The texture of soil is important because it determines a variety of physical qualities and imposes constraints on agricultural management approaches. As a result, soil texture plays a basic yet crucial function in developing regional agricultural methods and is a fundamental component to consider for both farmers and land managers. The role of soil structure on root development is documented on some plants while it is still not well-known on many (Centenaro et al., 2017; Wendel et al., 2022). The classification of soil texture can directly impact various essential functions, such as the capacity for holding water, drainage efficiency, active nutrient retention, and overall exchange capacity. These functions play a vital role in maintaining plant survival, contributing to higher crop yields while also improving soil quality. Gaining a deeper understanding of these processes remains a key focus in research, particularly in the study of soil texture and its interaction with the broader soil-plant system (Amsili et al., 2021; Gürsoy, 2021; Santos et al., 2021). This study examines wheat varieties with different root traits grown in soils of varying textures (heavy, medium, and light) to analyze root characteristic changes.

Material and Methods

The study aimed to determine the role of soil type and structures on root development on two different wheat cultivars (Saraybosna and Alparslan) with contrasting root and shoot properties. For this purpose, soils of different texture classes (sandy, loamy, and clayey) were collected from three distinct agricultural sites within the Van Lake Basin: sandy soil from Erciş plain, loamy soil from Edremit plain, and clayey soil from Van central. These soils were then air-dried, sieved using a 2 mm sieve, and packed into PVC tubes measuring 25 cm in length and 5 cm in width. Each tube had an approximate volume of 1.2 L, and soils were added until a 3 cm gap remained at the top after settling. After filling, water was added to each tube and left to settle for a specified period to reach the field capacity. Additional soil was then added to compensate for the settled portion, ensuring a 3 cm gap remained at the top of each tube. The physical and chemical properties of the soils used in the study are presented in Table 1. To standardize soil moisture, the tubes were saturated with water and then allowed to drain in order to reach field capacity. Although field capacity and wilting point were not separately measured for each soil type, all PVC tubes were irrigated uniformly at regular intervals to maintain adequate moisture throughout the experiment. Thus, irrigation scheduling was identical for all soil texture groups, ensuring that the observed differences in root traits were due to soil texture rather than water availability.

Table 1. Some physical and chemical properties of the soils used in the study.

Parameters	Sandy Soil	Loam Soil	Clayey Soil	Reference
Texture	% 63.00 sand % 19.00 clay % 18.00 silt	% 37.00 sand % 24.00 clay % 39.00 silt	% 38.00 sand % 48.00 clay % 14.00 silt	Tüzüner, 1990
pH	8.01	8.01	8.23	Richards, 1954
EC (dS m^{-1})	0.137	0.137	0.213	Richards, 1954
$CaCO_3$ (%)	4.89	3.20	6.11	Soil Survey Staff, 1993
Organic Matter (%)	1.54	1.66	1.87	Jackson, 1958
Phosphorus (mg kg^{-1})	3.20	3.86	4.17	Olsen, 1954
Nitrogen (%)	0.142	0.129	0.125	Kacar, 2009
Potassium (mg kg^{-1})	396	483	598	Jackson, 1958

The experiment included two wheat cultivars, Saraybosna and Alparslan, chosen based on previous studies evaluating root traits throughout the seedling stage (Özdemir, 2017). Saraybosna, which produces the most root biomass, and Alparslan, which has the least, were chosen. A total of thirty PVC tubes were employed, following a randomized complete blocks design with three types of soil, two wheat cultivars, and five replications. At the beginning of the experiment, three seeds were sown in each tube. After germination, the seedlings were removed to leave one plant per tube. Before the experiment, the nutrient status of each soil type was analyzed. The deficiencies identified in nitrogen, phosphorus, and potassium were corrected by applying ammonium sulfate, triple superphosphate, and potassium nitrate, respectively. The amounts of fertilizers applied were based on the soil analysis results for each texture group, ensuring that all treatments received equivalent nutrient availability. In this way, the nutrient supply was standardized across the three different soil textures, and no nutrient limitations affected the experiment.

The plants were harvested at the beginning of the tillering stage and during harvesting, plants were carefully removed from the PVC tubes and placed in a container filled with water. After soaking for a specified time, the softened roots were gently washed under running water using a 1mm sieve. The seedlings and roots were separated at the root collar, and measurements were taken on the

seedling portion. The root samples were then scanned using an A4 scanner with a resolution of The image analysis were performed an automated root image analyses software, RhizoVision explorer to assess root system characteristics (Seethepalli et al., 2021). Root morphological traits maximum root depth, total root length, root diameter, root volume and architectural traits SFW/RFW ratio, number of primary and lateral roots, root dry weight was evaluated. Variance analysis (ANOVA) was conducted to assess differences between groups, ensuring normality and homogeneity of variance assumptions were met before analysis. Principal Component Analysis (PCA) was used to identify key plant morphological traits, with all numerical variables standardized to eliminate scale differences. The findings were interpreted based on the biplot and PCA results. The obtained data was analyzed using SPSS 27.0 and R 4.1.2 with the FactoMineR 2.8, factoextra 1.0.7, and ggsci 2.9 packages (Lê et al., 2008; Kassambara, A., & Mundt, F., 2020; Field, 2024).

Results and Discussion

The results revealed that soil type and plant variety had significant effects on parameters such as seedling length, maximum root depth, seedling fresh weight, root fresh weight, seedling dry weight, root dry weight/seedling dry weight, total root length, primary and secondary root counts, root diameter, root volume, and root dry weight, all at a 1% error level. The interaction between soil type and variety was statistically significant for maximum root depth and root diameter, although all other parameters showed interactions.Understanding the roles and characteristics of root traits is a crucial step in advancing our knowledge in this field and for the possibility of utilizing root traits in plant breeding. Here in this study, we evaluated the effect of soil structure on root development using two different wheat cultivars with contrasting rooting patterns. With this goal in mind, the analysis of variance was performed to analyze the effects of different soil types and wheat varieties on various root and seedling characteristics. The results revealed that soil type and plant variety had significant effects on parameters such as seedling length, maximum root depth, seedling fresh weight, root fresh weight, seedling dry weight, root dry weight/seedling dry weight, total root length, primary and secondary root counts, root diameter, root volume, and root dry weight, all at a 1% error level. The interaction between soil type and variety was statistically significant for maximum root depth and root diameter, although all other parameters showed interactions. It is noteworthy that the variety × soil texture interaction was significant only for certain traits, such as maximum root depth and root diameter, whereas other parameters showed no significant interaction. This pattern likely reflects trait-dependent plasticity: depth and diameter are more sensitive to environmental drivers such as mechanical resistance and aeration, while traits like seedling length and (bulk) root volume tend to remain more stable across soil conditions. Similar conclusions about the role of soil physical constraints and trait-specific root plasticity have been drawn in wheat root studies (Lynch, 2013; Colombi et al., 2017; Atkinson et al., 2020)

Analysis of seedling lengths revealed that both varieties attained their highest values in sandy soil (Alparslan: 36.6 cm, Saraybosna: 36.4 cm), with an average of 36.5 cm (Figure 1, a). The lowest seedling length (20.76 cm) was recorded in the Alparslan variety grown in clay soil. The Duncan multiple comparison test confirmed significant differences among soil types, categorizing them into sandy, loamy, and clayey groups. Soil texture affects growth factors such as aeration, temperature, and microbial activity, which influence seedling height (Brady & Weil, 2016). Previous studies indicate that seedlings tend to grow taller in clay loam or sandy loam compared to pure sandy soils (Bengough et al., 2011). These findings are consistent with previous studies showing that reduced mechanical resistance in soil promotes root elongation by enabling easier penetration and reduced metabolic cost (Colombi et al., 2017; Lynch et al., 2014).

The maximum root depth varied by 9.73 cm between types, with Saraybosna performing best in sandy soil. (35.2 cm) (Figure 1, b). Alparslan had the shallowest roots in clay soil. Different wheat cultivars respond individually to soil conditions, with certain genotypes displaying better adaptability by producing deeper roots for enhanced water and nutrient absorption, hence increasing output (Hodgkinson et al., 2017).

Seedling fresh and dry weights were highest in sandy soil, though not significantly different from loamy soil (Figure 1; c,d). This suggests that better drainage and aeration in sandy and loamy soils benefit early seedling growth. However, factors like nutrient availability, water retention, and soil temperature also play crucial roles. The Alparslan variety had a lower seedling dry weight in clay soil, showing sensitivity to the increased density and lower oxygen levels. More research into these characteristics may provide deeper insights. (Abbas et al., 2018; Sweeney and Diaz, 2020).

The Saraybosna variety had the tallest root (693.2 mm) than Alparslan, with the highest value (813 mm) observed in Saraybosna planted on sandy soil (Figure 1, e). There was no significant difference between sandy and loamy soils, but both outperformed clayey soil. This shows that sandy and loamy soils are more conducive to root growth. Alparslan growing in clay soil had the shortest roots (263.8 mm). The literature supports the hypothesis that improving soil conditions promote root length by reducing mechanical resistance and increasing macropores, allowing roots to reach deeper (Colombi et al., 2017).

Saraybosna growing on clay soil had the most main and lateral roots (28.2), accounting for 12.14 more than Alparslan (Figure 1, f). Alparslan showed little variation across soil types, with root counts of 12.6, 11.8, and 11.4 in sandy, loamy, and clayey soils, respectively. Soil composition influences root system development and so shapes plant growth (Maffra et al., 2019; Ansari et al., 2021).

In terms of root diameter, sandy and loamy soils yielded better results (0.28 mm and 0.25 mm, respectively) than clayey soil (0.21 mm), though no significant difference was found between sandy and loamy soils (Figure 1, g). The increased root diameter observed in sandy and loamy soils may be due to lower mechanical impedance and improved aeration conditions, which allow roots to expand radially.

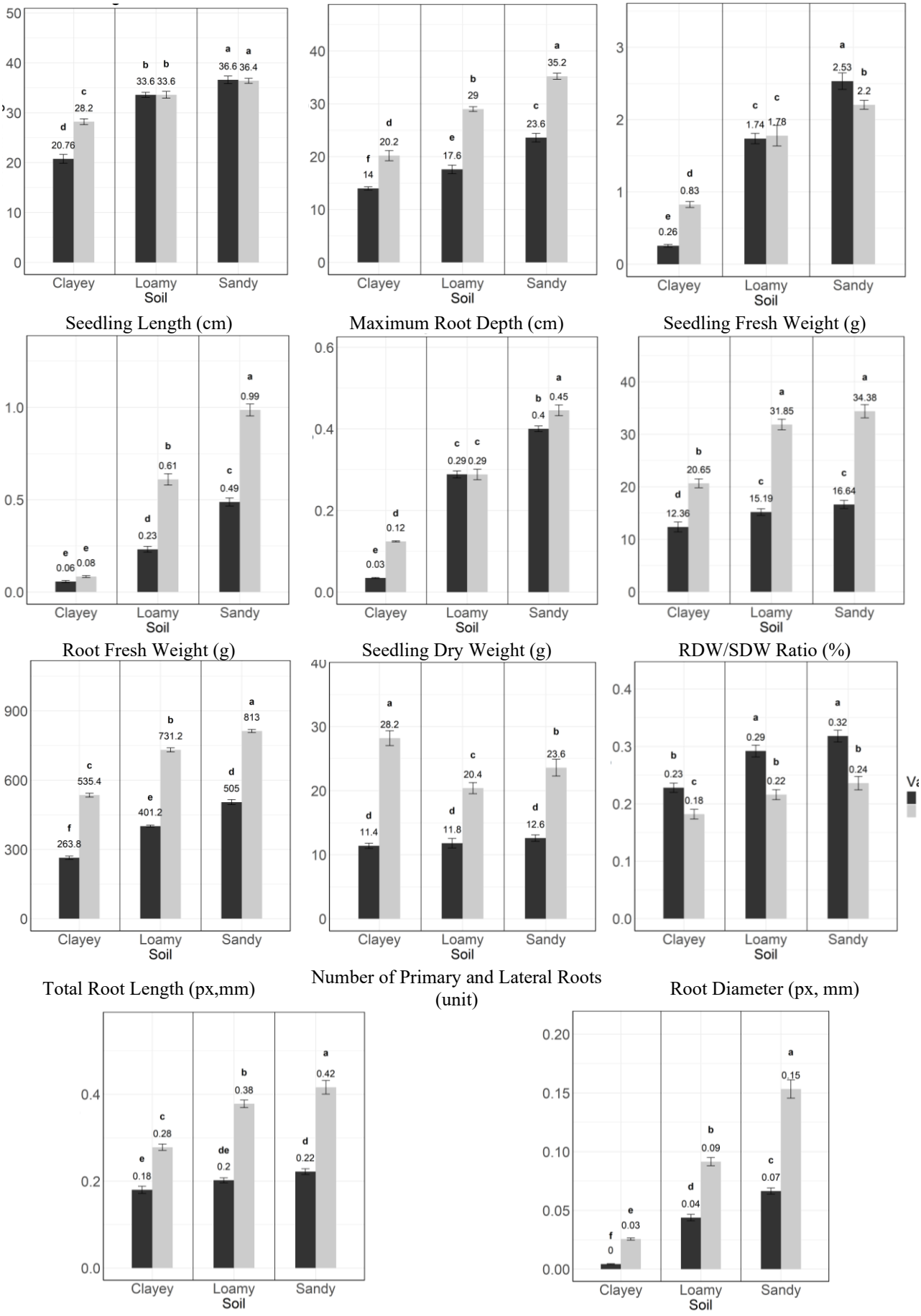

Figure 1. Variation in seedling for measured data. Numbers on the bars indicate mean values, and letters indicate Duncan's grouping at $p < 0.01$.

In contrast, compacted clayey soils with limited pore space and oxygen availability may restrict radial growth, resulting in thinner roots. Root diameter has been associated with the plant's ability to adapt to environmental stress, as thicker roots are often linked with enhanced structural stability and water transport efficiency (Colombi et al., 2017; Lynch, 2013). These findings suggest that soil texture influences not only root elongation but also anatomical traits like thickness, likely contributing to improved resource acquisition.

Saraybosna growing in sandy soil showed the largest root volume (0.42 cm^3). There was no statistical difference between sandy and loamy soils or loamy and clayey soils. However, sandy soil had a considerably higher root volume (0.32 cm^3) than clayey soil. Alparslan growing on clay soil has the smallest root volume. The significantly greater root volume observed in Saraybosna under sandy soil conditions may result from the lower bulk density and higher porosity of sandy soils, which facilitate both vertical and lateral root expansion. Higher root volume can improve water and nutrient absorption by increasing contact area with the surrounding soil matrix. On the contrary, the limited root volume observed in Alparslan under clayey soil likely results from higher compaction, reduced oxygen availability, and increased resistance to root penetration. These findings are supported by previous studies showing that root volume is highly sensitive to soil texture and structure, particularly under early growth conditions (Lynch, 2013; Gao et al., 2016).

Root dry weight was highest in Saraybosna grown in sandy soil (0.15 g), while Alparslan in clay soil had the lowest (0.004 g) (Figure 1, h). No significant difference was found between sandy and loamy soils. Soil compaction restricts root elongation and depth, as roots navigate lower resistance pathways such as pre-existing biopores (Atkinson et al., 2020).

The highest root dry weight/seedling dry weight ratio (RDW/SDW) was recorded in Saraybosna grown in sandy (34.38%) and loamy (31.85%) soils. Duncan's test indicated statistically significant differences between sandy and loamy soils, and between loamy and clayey soils, with sandy soil yielding the best results. The lowest ratio (12.36%) was found in Alparslan grown in clay soil. Soil texture influences this ratio by affecting water and nutrient availability and root penetration resistance. Poorly drained clay soils tend to favor shoot over root growth, leading to a higher top/root ratio. Well-drained soils, such as sandy and loamy types, generally support higher root dry weight relative to total seedling dry weight. Moisture availability further affects root-to-shoot ratios, highlighting the interplay between soil properties and plant development (Campbell and Jong, 2001; Colombi et al., 2017; Lynch, 2013; Atkinson et al., 2020)."

Principal Component and Correlation Analysis (PCA)

By jointly analyzing variety and soil characteristics, Principal Component Analysis (PCA) was conducted to determine the extent of variance explained in the dataset. The results identified two principal components that account for 91% of the total variation. Factors with eigenvalues exceeding 1 are deemed significant, and both components meet this criterion. The first principal component (PC1) predominantly influences root characteristics, with key contributing parameters including root age weight, root dry weight, maximum root depth, and total root length. PC1 largely accounts for variations in root traits. The second principal component (PC2) is primarily associated with root diameter and root count, showing a strong correlation with both. Some traits, such as seedling length, seedling fresh weight, and seedling dry weight, contribute to both components but are slightly more weighted toward PC1. Soil physical properties, particularly texture-related traits such as aeration and mechanical impedance, directly impact root diameter and root count, whereas characteristics like root biomass, dry weight, root depth, and length are more likely influenced by genetic factors (Dai et al., 2014; Zulqurnain et al., 2019)..

Features	PC1	PC2
Seedling Length	.799	.474
Seedling Fresh Weight	.759	.592
Root Fresh Weight	.953	.106
Seedling Dry Weight	.848	.500
Root Dry Weight	.969	.038
SFW/RFW Ratio	.884	-.387
Maximum Root Depth	.969	-.112
Total Root Length	.955	-.255
Number of Primary and Lateral Roots	.456	-.742
Root Diameter	.013	.963
Root Volume	.876	-.422
Seedling Length	.799	.474
Seedling Fresh Weight	.759	.592
Root Fresh Weight	.953	.106
Eigenvalue	7.39	2.72
Explained Variance (%)	67.16	24.75
Cumulative Variance (%)	67.16	91.91

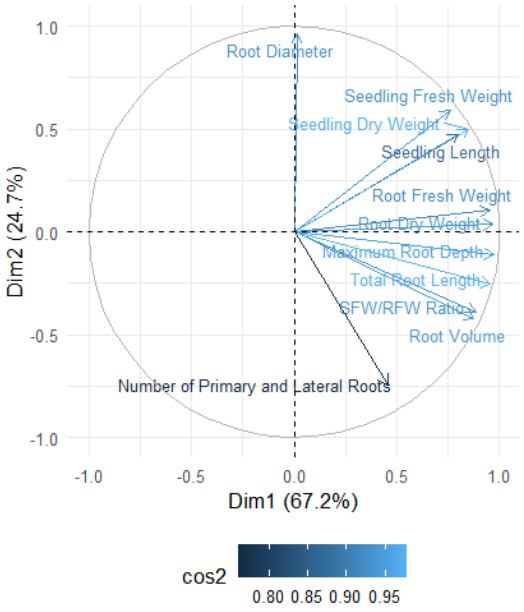

Figure 2. Principal Component Analysis (PCA) Biplot of Root and Seedling Traits

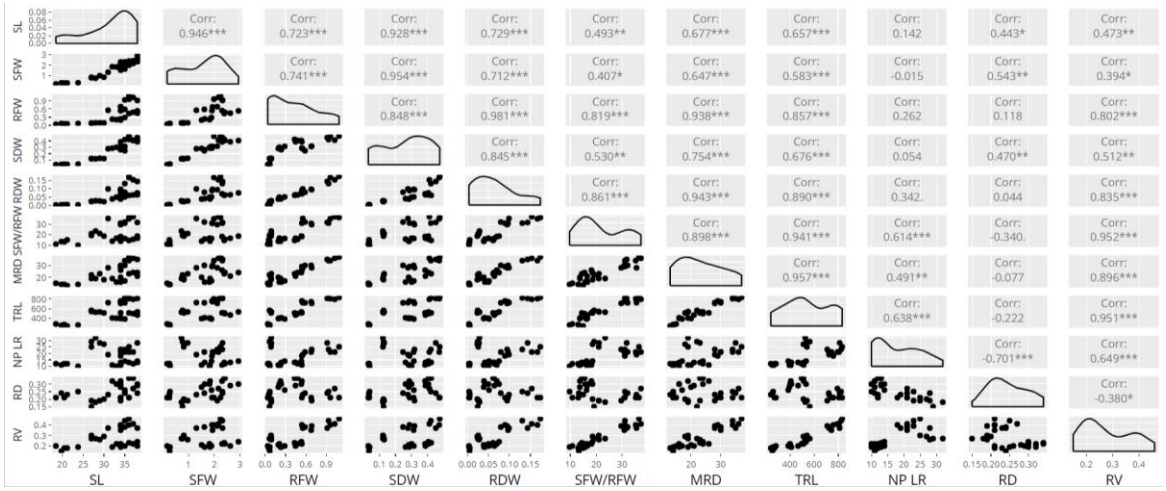

Figure 3. Correlation matrix of seedling and root traits in wheat

SL: Seedling Length, SFW: Seedling Fresh Weight, RFW: Root Fresh Weight, SDW: Seedling Dry Weight, RDW: Root Dry Weight, SFW/RFW Ratio, MRD: Maximum Root Depth, TRL: Total Root Length, NP LR: Number of Primary and Lateral Roots, RD: Root Diameter, RV: Root Volume

This overlap indicates that these seedling traits are correlated with both overall root size (captured by PC1) and root architecture (captured by PC2). In PCA, correlated variables may load on multiple components because each axis partitions variance along different dimensions. In our study, PC1 explained the main variation related to biomass and elongation traits, while PC2 represented variation in morphological traits such as diameter and branching. The fact that some traits load on both components reflects their multidimensional role in root system development.

A correlation analysis was performed to examine the relationships among the parameters in the study. The results indicate that many criteria are interconnected. Above-ground traits, including seedling length, fresh weight, and dry weight, are correlated with all factors except the number of primary and lateral roots (Ghimire et al., 2020). The analysis also reveals a strong relationship between root diameter and both the seedling fresh weight/root fresh weight ratio and maximum root depth. This suggests that a larger root diameter may enhance water and nutrient absorption, leading to increased seedling fresh weight, while also aiding deeper soil penetration (Comas et al., 2013; Lynch et al., 2014; Zhou et al., 2021). Additionally, the number of primary and lateral roots shows no correlation with most factors, except for the seedling fresh weight/root fresh weight ratio, maximum root depth, and total root length. The limited correlation of root count with other traits is particularly interesting, implying that while the sheer number of roots alone may not directly determine seedling growth, it contributes in combination with other characteristics such as depth and overall length. This highlights the complex interactions between various root traits and their collective influence on seedling development (Comas et al., 2013; Robinson et al., 2016).

Soil texture is one of the most critical environmental factors influencing root system development. Sandy soils, despite their low water-holding capacity, generally provide better aeration and reduced mechanical resistance compared to heavier soils, thereby facilitating root elongation and deeper penetration into the soil profile. This environment allows roots to explore greater soil volumes and enhances water and nutrient uptake efficiency (Bengough et al., 2011; White & Kirkegaard, 2010). In the present study, the superior root growth observed in sandy soils may be attributed to these favorable physical conditions, which reduce impedance at the root tip and promote root proliferation.

Conversely, clayey soils often restrict root growth due to their higher bulk density and compaction, which increase mechanical resistance and reduce pore connectivity. Although clay-rich soils can retain higher amounts of water and nutrients, the limited aeration and physical constraints tend to slow down root elongation and branching (Lipiec et al., 2012; Tracy et al., 2012). Loamy soils, by contrast, provide more balanced conditions in terms of water retention and aeration, creating intermediate root growth responses (Rich & Watt, 2013). These findings are consistent with our results, where genotypic differences were more pronounced under sandy conditions, indicating that soil texture strongly mediates root trait expression.

Conclusions

This study confirms that soil texture plays a significant role in wheat root development, with sandy and loamy soils providing more favorable conditions for root growth than clayey soil. The Saraybosna variety demonstrated superior root development across all soil types, particularly in sandy soil, where it achieved the highest root length, depth, and dry weight. In contrast, Alparslan showed reduced root growth in clayey soil, indicating its sensitivity to dense soil conditions. Soil texture influences root traits such as length, diameter, volume, and biomass, which are critical for water and nutrient uptake. The interaction between soil type and wheat variety significantly impacts root structure and overall plant performance. PCA highlighted root dry weight, maximum root depth, and total root length as the most influential factors in root development. These findings emphasize the importance of selecting suitable wheat varieties based on soil texture to enhance crop productivity. Future research should investigate the combined effects of soil texture, nutrient availability, and water retention on root development to improve our understanding of soil-plant interactions. Such insights could help optimize wheat cultivation in diverse soil environments, ultimately boosting agricultural sustainability and productivity.

Declarations

The authors declare that there are no competing interests. All authors contributed to the design, data collection, analysis, and manuscript writing, and approved the final version.

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