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Article

Evaluation of root morphology in banana genotypes under sodic soil stress using RhizoVision software

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Abstract: Banana (*Musa* spp.) productivity is limited by sodic soils, which impairs root growth and nutrient uptake. Analyzing root traits under stress conditions can aid in identifying tolerant genotypes. This study investigates the root morphological traits of banana cultivars under sodic soil stress conditions using Rhizovision software. The pot culture experiment was laid out in a Completely Randomized Design (CRD) under open field conditions, with treatments comprising the following varieties: Poovan (AAB), Udhayam (ABB), Karpooravalli (ABB), CO 3 (ABB), Kaveri Saba (ABB), Kaveri Kalki (ABB), Kaveri Haritha (ABB), Monthan (ABB), Nendran (AAB), and Rasthali (AAB), each replicated thrice. Parameters such as the number of roots, root tips, diameter, surface area, perimeter, and volume were assessed to evaluate the performance of different cultivars. The findings reveal that Karpooravali and Udhayam cultivars exhibited superior performance in terms of root morphology compared to other cultivars under sodic soil stress. These cultivars displayed increased root proliferation, elongation, and surface area, indicating their resilience to sodic soil stress. The utilization of Rhizovision software facilitated precise measurement and analysis of root traits, providing valuable insights into the adaptation mechanisms of banana cultivars to adverse soil conditions.

Keywords: banana; sodic soil; root growth; rhizovision software

1. Introduction

Banana, a vital fruit crop in India, is widely grown in tropical and subtropical regions. Originating from Southeast Asia, it belongs to the Musaceae family. Globally, bananas rank as the fourth-largest fruit crop, surpassing grapes, citrus, and apples. They are also the most valuable fruit commodity of export value [1]. India leads in banana production, yielding 34.53 million metric tonnes (Source: Statista, 2022), with Tamil Nadu ranking second in area and fourth in production.

Banana cultivation faces significant challenges, with soil salt stress emerging as a major issue impacting root structure, nutrient absorption, and agricultural productivity. Sodic soil poses significant challenges to achieving optimal crop yields due to its detrimental effects on soil properties, including compromised aeration, hindered root growth, and increased susceptibility to root diseases [2]. Excessive exchangeable sodium in sodic soils severely inhibits desirable plant development, hindering root penetration, nutrient uptake, and overall growth [2].

Root morphology plays a critical role in the health and productivity of plants, influencing essential functions like nutrient uptake, water absorption, and structural support [3,4]. Understanding how banana cultivars adapt their root structures to sodic soil stress is crucial for enhancing growth, yield, and quality. Recent advancements in root phenotyping, particularly with RhizoVision software, enable precise, non-destructive analysis of root architecture. RhizoVision facilitates the study of root responses to stresses like sodic soil, helping identify traits linked to tolerance. This approach enhances understanding of plant-root interactions and supports breeding resilient crop varieties for challenging soils.

In this investigation, we aim to assess the root morphological traits of different banana cultivars under sodic soil stress using Rhizovision software. By analyzing parameters such as root length, surface area, diameter and branching density, we seek to understand how banana roots respond to sodic soil conditions and identify cultivars with enhanced stress tolerance. With this view, the objectives of the study are to analyze the root morphological traits of banana genotypes under sodic soil stress using RhizoVision software and to evaluate the relationship between root traits and stress resilience for improved nutrient and water uptake.

2. Materials and methods

The present investigation on "Evaluation of Root Morphology in Banana Genotypes under Sodic Soil Using RhizoVision Software" was conducted at the Department of Fruit Science, Horticultural College and Research Institute for Women, Tamil Nadu Agricultural University, Trichy, during the year 2023–2024. The pot culture experiment was laid out in a Completely Randomized Design (CRD) under open field conditions, with treatments comprising the following varieties: Poovan (AAB), Udhayam (ABB), Karpooravalli (ABB), CO 3 (ABB), Kaveri Saba (ABB), Kaveri Kalki (ABB), Kaveri Haritha (ABB), Monthan (ABB), Nendran (AAB), and Rasthali (AAB), each replicated thrice. Kaveri Saba is considered the check variety.

2.1. Soil material

The pot culture experiment was carried out in sodic soil. The experimental soil was grouped as sodic soil based on the classification of the salt-affected soils [5]. The physical and chemical properties of the soil of the experimental plot were analyzed before the start of the experiment, and data are presented in **Table 1**.

Table 1. Soil characteristics of the experimental plot.

Chemical properties	**Value**
pH	8.70
EC (S/m)	0.50
Available *N* (Kg/ha)	100.35
Available *P* (Kg/ha)	10.08
Available *K* (Kg/ha)	189.20
Exchangeable sodium percentage [ESP] (%)	20.89

2.2. Pot experiment

The experiment was conducted under open field conditions, with sodic soil filled in polybags measuring 16 cm (diameter) × 45 cm (height) × 16 cm (depth). Three months after planting, the plants were uprooted and divided into root and shoot components. Root parameters such as root length, number of roots, root diameter, perimeter, volume, and surface area were assessed using rhizovision software.

2.3. Image acquisition and setting values in Rhizovision software

The roots of ten varieties were scanned and uploaded in the software RhizoVision Explorer (© Noble Research Institute, LLC). The parameter settings used in the Root Visualization Environment (RVE) for analyzing root morphological traits. The thresholding level was set at 220 to ensure accurate detection of root structures. Particles smaller than 1 mm were filtered out to minimize noise and focus on significant root elements. A root-pruning threshold of 5 was applied to remove minor root segments that could interfere with the analysis. Additionally, root diameters were categorized into two classes: 2 mm to 5 mm and those exceeding 5 mm, allowing for a more detailed examination of root thickness variations. The other features and the description are followed by Seethepalli et al. [6].

2.4. Statistical analysis

The experiment was set up in a Completely Randomized Design (CBD) with ten treatments (genotypes) replicated thrice (per replication, two plants). A one-way analysis of variance (ANOVA) was performed. The significant result is indicated when means were compared using LSD (Least Significance Difference) and the resulting P-value was <0.05. Statistical analysis was performed with the AGRESS Software.

3. Results and discussion

Significant variations in maximum root numbers were noted among banana genotypes under sodic soil stress (**Table 2**). Excessive salinity alters root architecture, impacting water and nutrient uptake efficiencies [7,8]. Udhayam (ABB) showed the highest mean root number (28), indicating robust proliferation, while K. Haritha (ABB) exhibited the lowest [9]. These findings underscore the importance of root traits in stress tolerance and the potential of specific genotypes for efficient soil exploration. The use of Rhizovision software facilitated precise root analysis for genotype selection.

Table 2. Effect of sodicity in banana genotypes on the number of roots, root tips and root length.

Varieties (Genotypes)	Maximum Number of Roots	Number of Root Tips	Total Root Length (mm)
T_1 Poovan (AAB)	23	105	379.75
T_2 Udhayam (ABB)	28	125	592.99
T_3 Karpooravalli (ABB)	20	90	491.30
T_4 K. Saba (ABB)	15	54	262.85

Table 2. (*Continued*).

Varieties (Genotypes)	Maximum Number of Roots	Number of Root Tips	Total Root Length (mm)
T_5 CO 3 (ABB)	20	82	392.67
T_6 K. Haritha (ABB)	9	50	167.91
T_7 K. Kalki (ABB)	16	51	223.01
T_8 Monthan (ABB)	14	37	240.25
T_9 Nendran (AAB)	10	27	127.79
T_{10} Rasthali (AAB)	11	41	131.16
Mean	16.6	66.2	300.968
SEd	0.232	1.069	2.662
CD @ 5%	0.685**	3.154**	7.854**

** Highly significant at 0.05%.

Significant variations were noted in root tip numbers among banana genotypes under sodic soil stress (**Table 2**). Udhayam (ABB) showed the highest mean number (125), followed by Poovan (AAB) and Karpooravalli (ABB) with 105 and 90 root tips, respectively, indicating extensive root branching for efficient soil exploration. Conversely, Nendran (AAB) exhibited the lowest mean number (27), reflecting limited root branching. Monthan (ABB) and Rasthali (AAB) also showed relatively few root tips (**Figure 1**).

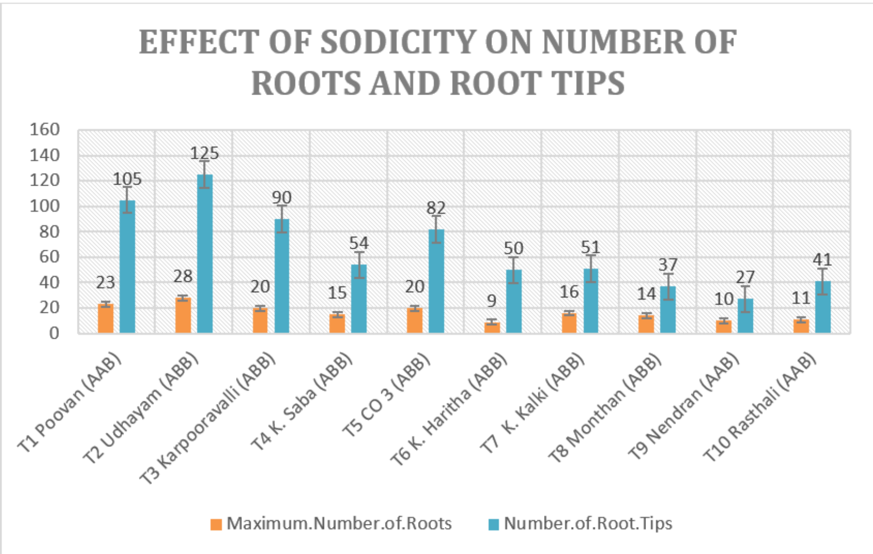

Figure 1. Effect of sodicity on the number of roots, root tips.

Significant variations were evident in total root length among banana genotypes under sodic soil stress (**Table 2**). Udhayam (ABB) exhibited the longest mean length (592.99 mm), followed by Karpooravalli (ABB) and Poovan (AAB) with 491.3 mm and 379.75 mm, respectively, indicating extensive root growth for efficient soil exploration. Conversely, Nendran (AAB) had the shortest mean length (127.79 mm), reflecting limited root elongation. Similarly, Rasthali (AAB) and K. Haritha (ABB) also showed relatively shorter lengths. Ample moisture availability promotes rapid cell elongation, facilitating longer roots, as observed [9]. Reduced root length under salt stress has also been reported by several studies [10–13].

Table 3. Effect of sodicity in banana genotypes on depth, network area and lower root area.

Varieties (Genotypes)	Depth (mm)	Network Area (mm^2)	Lower Root Area (mm^2)
T_1 Poovan (AAB)	19.515	103.903	69.130
T_2 Udhayam (ABB)	37.888	151.462	105.616
T_3 Karpooravalli (ABB)	40.894	154.428	46.279
T_4 K. Saba (ABB)	28.321	104.460	88.438
T_5 CO 3 (ABB)	46.566	106.386	92.275
T_6 K. Haritha (ABB)	35.263	50.580	22.098
T_7 K. Kalki (ABB)	14.520	63.207	22.935
T_8 Monthan (ABB)	18.034	81.689	46.295
T_9 Nendran (AAB)	46.947	53.245	33.349
T_{10} Rasthali (AAB)	13.970	34.184	7.573
Mean	30.191	90.354	53.398
SEd	0.505	1.242	1.16
CD @ 5%	1.491**	3.665**	3.422**

** Highly significant at 0.05%.

Significant variations in root depth were observed among banana genotypes under sodic soil stress (**Table 3**). Karpooravalli (ABB) showed the deepest mean depth (40.894 mm), followed by Nendran (AAB) (46.947 mm) and CO 3 (ABB) (46.566 mm), indicating their ability to penetrate deeper soil layers for moisture and nutrients. Conversely, Rasthali (AAB) and K. Kalki (ABB) exhibited the shallowest depths (13.97 mm and 14.52 mm), suggesting limited soil penetration. Udhayam (ABB) also had a relatively shallow depth (37.888 mm). Thicker roots may aid in penetrating hard or clayey soils to access water in deeper layers [14].

Karpooravalli (ABB) had the largest root network area (154.428 mm^2), followed by Udhayam (ABB) with 151.462 mm^2, and CO 3 (ABB) with 106.386 mm^2. These genotypes efficiently explored soil and acquired resources. Conversely, Rasthali (AAB) and K. Kalki (ABB) showed smaller areas (34.184 mm^2 and 63.207 mm^2), indicating limited soil exploration. Similarly, K. Haritha (ABB) had a relatively smaller area (50.58 mm^2) compared to others (**Table 3**).

Udhayam (ABB) displayed the largest lower root area (105.616 mm^2), followed by CO 3 (ABB) (92.275 mm^2) and K. Saba (ABB) (88.438 mm^2), indicating efficient soil exploration for nutrient and water uptake (**Table 3**). Conversely, Rasthali (AAB) and K. Kalki (ABB) had the smallest lower root areas (7.573 mm^2 and 22.935 mm^2, respectively), suggesting limited exploration in deeper soil layers. K. Haritha (ABB) also exhibited a relatively smaller lower root area (22.098 mm^2) (**Figure 2**). High concentrations of salt have been shown to negatively impact root growth, leading to a rapid reduction in primary root depth, including total root length, root number, root surface area, and volume [15–17].

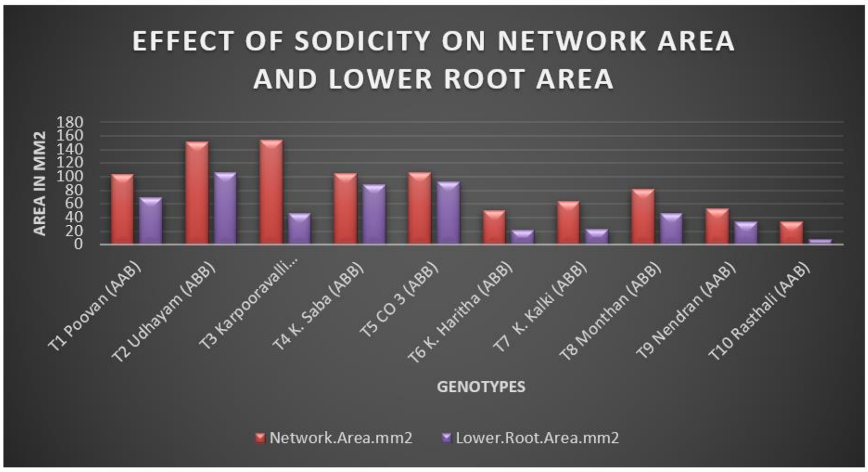

Figure 2. Effect of sodicity on network area and lower root area.

Nendran (AAB) displayed the largest mean average root diameter (0.841 mm), followed by K. Saba (ABB) with 0.872 mm and Monthan (ABB) with 0.671 mm. These genotypes had thicker root diameters, potentially enhancing structural stability and stress tolerance. Conversely, Rasthali (AAB) exhibited the smallest mean average root diameter (0.392 mm), indicating thinner root structures. Poovan (AAB) also had a relatively small mean average root diameter (0.45 mm). The variation in average root diameter underscores genetic diversity in root morphology. Thicker roots, as seen in Nendran (AAB), K. Saba (ABB), and Monthan (ABB), could provide benefits in mechanical support and nutrient uptake under sodic soil stress.

Nendran (AAB) exhibited the largest mean maximum root diameter (3.922 mm), followed by K. Saba (ABB) (3.726 mm) and Karpooravalli (ABB) (3.39 mm), indicating thicker root structures beneficial for nutrient acquisition and structural support under sodic soil stress (**Table 4**). Conversely, Rasthali (AAB) displayed the smallest mean maximum root diameter (1.949 mm), suggesting thinner root structures. Udhayam (ABB) and K. Haritha (ABB) also exhibited smaller mean maximum root diameters compared to Nendran (AAB) and other genotypes. The variation in maximum root diameter underscores genetic diversity in root morphology and adaptation to sodic soil stress. Thicker roots, as observed in Nendran (AAB), K. Saba (ABB), and Karpooravalli (ABB), may facilitate soil exploration and nutrient uptake, contributing to enhanced plant growth and productivity under sodic soil conditions. Thicker roots could aid in penetrating hard or clayey soils to access water in deeper soil layers, as suggested by Clark et al. [14].

Udhayam (ABB) showed the largest mean root perimeter (783.316 mm), followed by Karpooravalli (ABB) (631.241 mm) and Poovan (AAB) (540.772 mm), indicating larger root perimeters and potential advantages in root surface area and nutrient uptake efficiency under sodic soil stress (**Table 4**). Conversely, Nendran (AAB) exhibited the smallest mean root perimeter (154.158 mm), suggesting a comparatively lower root surface area. Rasthali (AAB) and K. Haritha (ABB) also displayed smaller mean root perimeters compared to Udhayam (ABB) and other genotypes. The diversity in root perimeter among banana genotypes underscores their varied root morphology and adaptation to sodic soil stress (**Figure 3**). Genotypes with larger root perimeters, such as Udhayam (ABB) and Karpooravalli

(ABB), may benefit from enhanced nutrient acquisition and water uptake, contributing to improved plant growth and productivity in sodic soil conditions.

Table 4. Effect of sodicity in banana genotypes on average and maximum diameter and perimeter.

Varieties (Genotypes)	Average Diameter (mm)	Maximum Diameter (mm)	Perimeter (mm)
T_1 Poovan (AAB)	0.450	2.794	540.772
T_2 Udhayam (ABB)	0.448	2.443	783.316
T_3 Karpooravalli (ABB)	0.531	3.390	631.241
T_4 K. Saba (ABB)	0.872	3.726	305.174
T_5 CO 3 (ABB)	0.463	2.768	527.072
T_6 K. Haritha (ABB)	0.507	2.287	236.454
T_7 K. Kalki (ABB)	0.511	2.690	302.992
T_8 Monthan (ABB)	0.671	3.581	298.214
T_9 Nendran (AAB)	0.841	3.922	154.158
T_{10} Rasthali (AAB)	0.392	1.949	210.919
Mean	0.568	2.955	399.031
SEM	0.008	0.03	6.928
CD @5%	0.024**	0.091**	20.439**

** Highly significant at 0.05%.

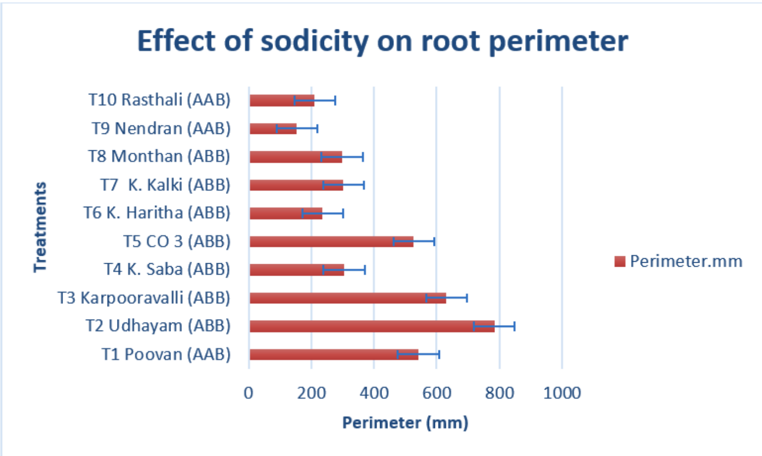

Figure 3. Effect of sodicity on root perimeter.

K. Saba (ABB) exhibited the highest mean root volume (327.972 mm^3), followed by Karpooravalli (ABB) (229.241 mm^3) and Udhayam (ABB) (168.924 mm^3) indicating larger root volumes and potential advantages in water and nutrient absorption efficiency under sodic soil stress. In contrast, Rasthali (AAB) displayed the lowest mean root volume (30.717 mm^3), suggesting limited root development compared to other genotypes. K. Haritha (ABB) and CO 3 (ABB) also showed relatively smaller mean root volumes compared to K. Saba (ABB) and Karpooravalli (ABB). The diversity in root volume among banana genotypes reflects genetic variation in root morphology and adaptation to sodic soil stress (**Table 5**). Genotypes with larger root volumes may benefit from enhanced nutrient and water uptake, contributing to improved plant growth and productivity under sodic soil conditions.

K. Saba (ABB) had the highest mean root volume (327.972 mm^3), followed by Karpooravalli (ABB) (229.241 mm^3) and Udhayam (ABB) (168.924 mm^3) indicating larger root volumes and potential advantages in water and nutrient absorption efficiency under sodic soil stress. Conversely, Rasthali (AAB) showed the lowest mean root volume (30.717 mm^3), suggesting limited root development compared to other genotypes. K. Haritha (ABB) and CO 3 (ABB) also displayed relatively smaller mean root volumes compared to K. Saba (ABB) and Karpooravalli (ABB). This diversity in root volume (**Figure 4**) among banana genotypes reflects genetic variation in root morphology and adaptation to sodic soil stress, with larger root volumes potentially contributing to improved plant growth and productivity under such conditions (**Table 5**).

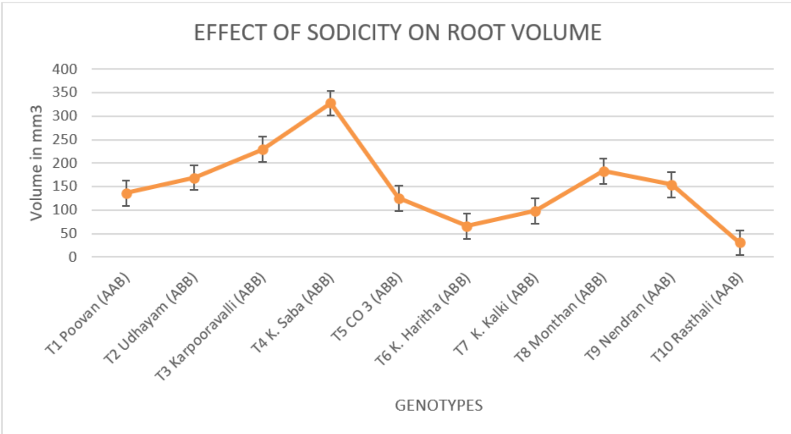

Figure 4. Effect of sodicity on root volume.

Table 5. Effect of sodicity in banana genotypes on volume, surface area and average root orientation.

Varieties (Genotypes)	Volume (mm^3)	Surface Area (mm^2)	Average Root Orientation (deg)
T_1 Poovan (AAB)	136.399	535.822	37.153
T_2 Udhayam (ABB)	168.924	830.539	50.688
T_3 Karpooravalli (ABB)	229.241	829.059	48.858
T_4 K. Saba (ABB)	327.972	720.652	51.225
T_5 CO 3 (ABB)	125.329	570.625	52.793
T_6 K. Haritha (ABB)	65.989	267.335	54.706
T_7 K. Kalki (ABB)	98.457	359.310	32.445
T_8 Monthan (ABB)	182.647	508.318	49.624
T_9 Nendran (AAB)	154.072	336.721	52.635
T_{10} Rasthali (AAB)	30.717	160.782	37.241
Mean	151.974	511.916	46.736
SEM	3.021	9.440	0.677
CD @5%	8.911**	27.850**	1.997**

** Highly significant at 0.05%.

K. Kalki (ABB) had the lowest mean root angle (32.445°), favoring vertical growth for deeper soil penetration (**Table 5**). Conversely, K. Haritha (ABB) had the highest angle (54.706°), suggesting horizontal growth limiting deep soil exploration.

Udhayam (ABB), Karpooravalli (ABB), and K. Saba (ABB) displayed intermediate angles, indicating a mix of vertical and horizontal growth patterns. These variations in root angles among genotypes reflect diverse strategies for nutrient and water uptake in sodic soil stress.

Udhayam (ABB) exhibited the widest root diameter range (592.992 mm), indicating varied root thickness. This diversity could enhance nutrient and water uptake efficiency. Conversely, Nendran (AAB) and Rasthali (AAB) had narrower ranges (127.799 mm and 131.167 mm, respectively), potentially limiting soil exploration. The root diameter range diversity reflects adaptation strategies to sodic soil stress, with wider ranges offering advantages in nutrient uptake and stress tolerance.

Udhayam (ABB) showed the widest projected area diameter range (264.251 mm^2), suggesting varied root thickness and spatial distribution (**Table 6**). This diversity likely enhances soil exploration and nutrient uptake efficiency. Conversely, Rasthali (AAB) exhibited the narrowest range (51.178 mm^2), possibly limiting its ability to access resources from different soil depths. The observed variation underscores genetic diversity in root morphology and distribution strategies under sodic soil stress, with wider ranges offering advantages in nutrient acquisition and stress tolerance.

Table 6. Effect of sodicity in banana genotypes on root length diameter range and projected area diameter range.

Varieties (Genotypes)	Root Length Diameter Range (mm)	Projected Area Diameter Range (mm^2)
T_1 Poovan (AAB)	379.758	170.505
T_2 Udhayam (ABB)	592.992	264.251
T_3 Karpooravalli (ABB)	491.308	263.842
T_4 K. Saba (ABB)	262.857	229.390
T_5 CO 3 (ABB)	392.674	181.635
T_6 K. Haritha (ABB)	167.915	85.075
T_7 K. Kalki (ABB)	223.010	114.338
T_8 Monthan (ABB)	240.255	161.763
T_9 Nendran (AAB)	127.799	107.117
T_{10} Rasthali (AAB)	131.167	51.178
Mean	300.973	162.909
SEM	6.14	2.901
CD @5%	18.113**	8.560**

** Highly significant at 0.05%.

Udhayam (ABB) demonstrated the widest surface area diameter range (830.539 mm^2), suggesting diverse root spread and distribution (**Table 7**). This variability likely enhances soil exploration and nutrient uptake efficiency. Conversely, Rasthali (AAB) showed the narrowest range (160.782 mm^2), possibly limiting its ability to access resources from various soil depths. The observed diversity underscores genetic variations in root morphology and spatial distribution strategies under sodic soil stress, with wider ranges offering advantages in nutrient acquisition and stress tolerance. **Figure 5** depicts the images of the root by Rhizovision software.

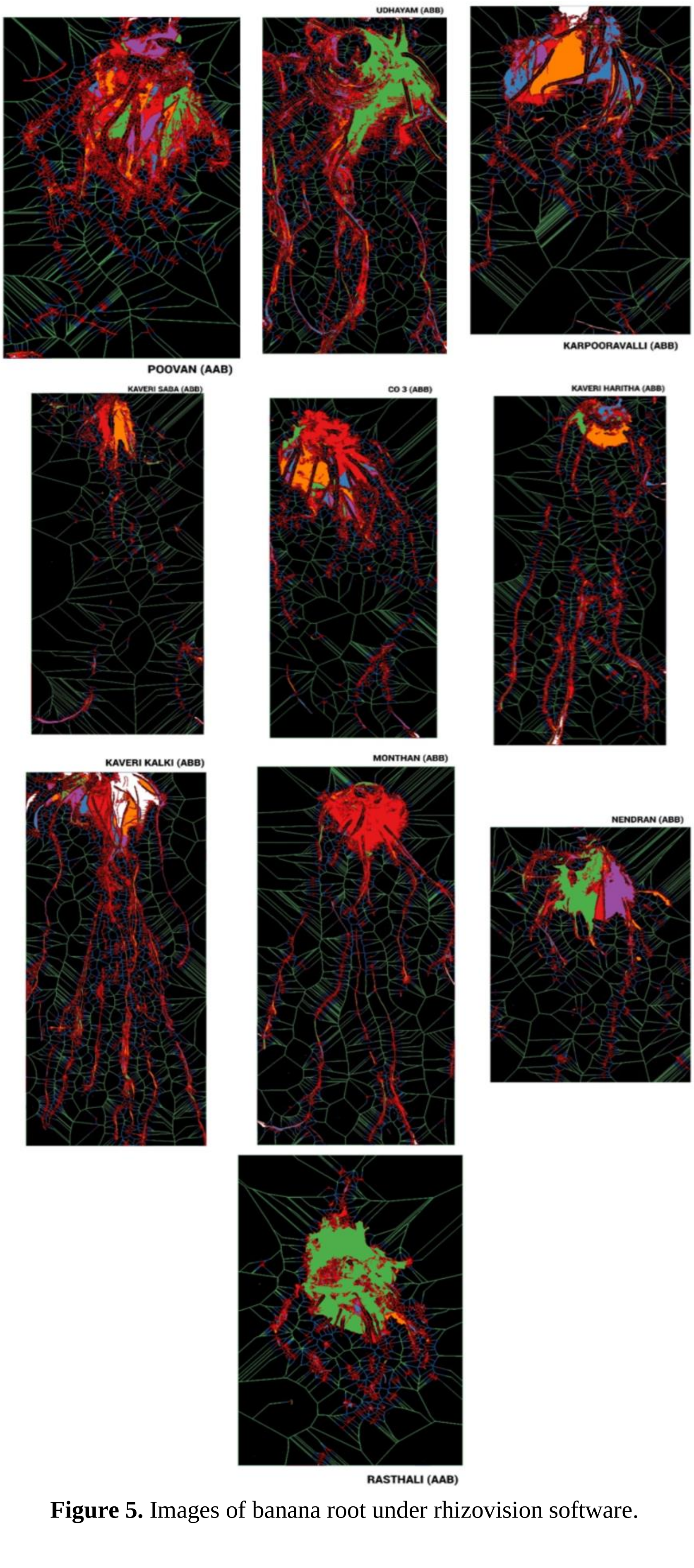

Figure 5. Images of banana root under rhizovision software.

K. Saba (ABB) demonstrated the widest volume diameter range (327.972 mm^3), indicating diverse root thickness and distribution (**Table 7**). This variability likely enhances soil exploration and nutrient uptake efficiency. Conversely, Rasthali (AAB) showed the narrowest range (30.717 mm^3), potentially limiting its ability to access resources from various soil depths. This diversity underscores genetic variations in root morphology and spatial distribution strategies under sodic soil stress, with wider ranges offering advantages in nutrient acquisition and stress tolerance. **Figure 6** depicts the pot cultivation of different banana varieties.

Table 7. Effect of sodicity in banana genotypes on surface area diameter range and volume diameter range.

Varieties (Genotypes)	Surface Area Diameter Range (mm^2)	Volume Diameter Range (mm^3)
T_1 Poovan (AAB)	535.822	136.399
T_2 Udhayam (ABB)	830.539	168.924
T_3 Karpooravalli (ABB)	829.059	229.241
T_4 K. Saba (ABB)	720.652	327.972
T_5 CO 3 (ABB)	570.625	125.329
T_6 K. Haritha (ABB)	267.335	65.989
T_7 K. Kalki (ABB)	359.31	98.457
T_8 Monthan (ABB)	508.318	182.647
T_9 Nendran (AAB)	336.721	154.072
T_{10} Rasthali (AAB)	160.782	30.717
Mean	511.916	151.974
SEM	9.714	2.114
CD @5%	28.657**	6.237**

** Highly significant at 0.05%.

Figure 6. Pot cultivation of different banana varieties.

4. Conclusion

In conclusion, our study demonstrates the importance of root morphological traits in conferring tolerance to sodic soil stress in banana cultivars. Karpooravali and Udhayam cultivars exhibited enhanced root proliferation, elongation, and surface area, suggesting their ability to adapt and thrive under sodic soil stress conditions. RhizoVision software enabled precise analysis of root traits, offering insights into banana root responses to soil stress. These findings support breeding programs to develop resilient cultivars, ensuring sustainable banana production in sodic soil-affected regions.

Author contributions: Project administration, VJ; supervision, VJ; formal analysis, JK; the original draft of the manuscript, JK; software and methodology, KRV. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest: The authors declare no conflict of interest.

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