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RESEARCH ARTICLE

Xylem vessel morphology of pigeon pea (*Cajanus cajan*) under drip and surface irrigation using scanning electron microscopy

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Abstract

The study aimed to analyze the morphological attributes of the root and stem xylem diameter of pigeon pea through scanning electron microscopy to understand its structural and functional characteristics under varying conditions and provide significant insights into the structural variations caused by different irrigation methods. Through Scanning electron microscope imaging, distinct differences in vessel architecture, such as size and wall thickness, were observed in root and stem, which may impact water and nutrient transportation efficiency and overall plant health. These variations are vital for understanding how irrigation strategies affect the physiological function and adaptation of pigeon pea, providing crucial information for improving agricultural practices and enhancing crop yield in varying environmental conditions. The results emphasize the importance of optimizing irrigation methods to promote better vascular development in crops, ultimately leading to sustainable agricultural practices. Scanning electron microscopy images revealed distinct differences in xylem vessel structure between drip and surface irrigation of pigeon peas.

Keywords: pigeon pea; root and stem xylem diameter; SEM analysis

Introduction

Pigeon pea (*Cajanus cajan* L.) is a legume crop commonly grown in tropical and subtropical climate, is highly valued for high protein (21 %) which contributes known for its adaptability and nutritional significance, particularly in tropical and subtropical regions (1). As one of the oldest cultivated legumes, pigeon pea has been integral to food security for millions of people, providing a rich source of protein, essential amino acids and dietary fiber (2). India is the largest producer of pigeon pea accounting for about 80 % of the total world pigeon pea production. In India, it occupies an area of 3.71 mha, with a production and productivity of 2.78 mt. and 750 kg ha^{-1} respectively (3). Drip irrigation is a modern agricultural technique that has gained prominence in pigeon pea cultivation due to its effectiveness in optimizing water use and enhancing crops. The traditional methods of irrigation, such as furrow and flood irrigation, often lead to inefficient water usage, which is unsustainable in regions facing water scarcity. Drip irrigation delivers water directly to the root zone of the plants, minimizing evaporation and runoff, which are common issues in conventional irrigation methods (4). This method conserves water and ensures that plants receive consistent moisture, which is crucial at various growth stages, including germination, flowering and pod formation. During these critical phases, adequate irrigation is essential to prevent yield loss, flower drop and pod cracking. Furthermore, drip irrigation can reduce the incidence of foliar diseases, such as blight, which can significantly affect pigeon pea crops. By maintaining optimal soil moisture levels, farmers can promote healthier plant growth and improve the overall quality of their harvest (5).

The adoption of drip irrigation fosters sustainable agricultural practices by improving water utilization efficiency and reducing the amount of water needed compared to traditional methods (6). It also encourages sustainable crop production by enabling farmers to manage their resources effectively, ensuring a successful pigeon pea harvest while conserving water. As global water resources become increasingly strained, implementing drip irrigation systems for pigeon pea cultivation represents a viable solution to enhance agricultural productivity and sustainability in the face of environmental challenges. Drip irrigation has garnered significant attention in agricultural practices due to its potential to enhance water use efficiency and improve crop yield (7). The impact of this irrigation method on the anatomical adaptation of plants, specifically xylem vessel size, is crucial for understanding plant responses to water availability and optimizing irrigation strategies. This discussion delves into the specific effects of drip irrigation on xylem vessel size in roots and overall plants, comparing these outcomes with other irrigation methods such as flood irrigation, sprinkler irrigation and furrow irrigation. Therefore, farmers are switching over to drip irrigation to improve irrigation efficiency and water productivity (8). Xylem vessels play a pivotal role in the transport of water and nutrients from roots to aerial parts of the plant (9-10). The size and density of these vessels can significantly influence a plant's water transport efficiency and hydraulic safety. Different irrigation methods create distinct soil moisture conditions, which can lead to physiological and anatomical changes in plants (11). Drip irrigation, characterized by localized water application directly to the root zone, is expected to induce unique adaptations in xylem vessel dimensions compared to more traditional methods like flood or sprinkler irrigation, which result in more uniform wetting patterns across the soil area.

Materials and Methods

Field and Experimental details

Field tests were conducted at the Millet Breeding Station, field No. 2G, at Tamil Nadu Agricultural University in Coimbatore. Drip irrigation at 100 % RDF using WSF (Water Soluble Fertilizer) and 100 % WRc (Crop water requirement) and surface irrigation using conventional fertilizer and IW/CPE 0.6 (Irrigation Water/ Cumilative Pan Evaporation) were tested on the short-duration and photo-insensitive pigeon pea (*Cajanus cajan* L.) varieties such as Co (Rg) 7, APK 1 and VBN 3. The varieties are wire-planted with paired row plantings of 90/60x30 cm and have a 120-day lifespan. The plant is taken for approximately 90 days old and in the pod formation stage because the uptake will be more in this stage.

Scanning Electron Microscope (SEM)

The steps involved in SEM sample preparation include surface cleaning, stabilizing the sample with a fixative (Glutaraldehyde (2 -5 %) rinsing, dehydrating, drying and mounting the specimen on a metal holder. Transverse hand sections, approximately 0.2 to 0.5 mm thickness were made with a razor blade for roots, stem and leaf taken for Scanning Electron Microscopy (SEM) using a FEI QUANTA 250 ESSEM.

Results and Discussion

In the exploration of xylem vessel size and its implications under varying irrigation conditions, the pigeon pea (*Cajanus cajan*) provides critical case study, particularly in understanding how changes in hydraulic architecture can enhance water status, nutrient absorption and overall plant health.

Xylem vessel dimensions play a vital role in plant root hydraulic conductivity larger vessels (75.37 + 61.26 µm) facilitate greater water transport and nutrients, while smaller vessels help to minimize cavitation risk during drought stress. In the treatment optimal conditions of drip irrigation specifically at 100 % water requirement, it is expected to observe a predominance of larger xylem vessels, which would theoretically promote enhanced water transport efficiency and nutrients. This is crucial for supporting leaf transpiration and maintaining physiological processes essential for growth. However, it is critical to consider the evolutionary adaptations that pigeon pea exhibit in response to fluctuating water availability and nutrient absorption (12).

The morphology of root xylem vessels is not merely a function of water availability but is also influenced by genetic factors and environmental conditions, indicating a degree of phenotypic plasticity. Pigeon pea plants may adjust their xylem vessel size in response to drip irrigation techniques, potentially modifying vessel dimensions during periods of adequate water supply and nutrients compared to surface irrigation (Table 1). This adaptability can be explored through reciprocal transplant experiments, which elucidate how vessels from plants grown in consistently irrigated conditions differ from those subjected to water deficits.

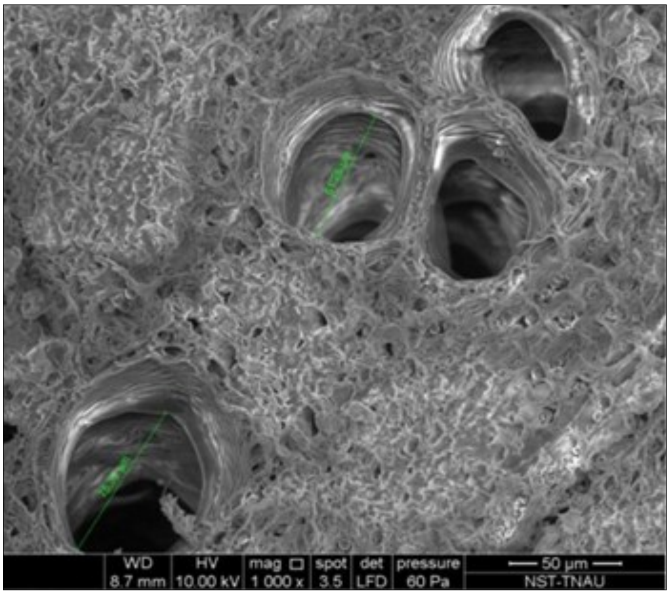
SEM (Fig. 1) images reveal significant differences in the anatomical structure of the root xylem cross sections diameter of pigeon pea under the drip irrigation method. The whole view of the roots demonstrates a greater size and robust development of tracheary cells when subjected to drip irrigation at 100 % water requirement compared to those under surface irrigation. The SEM images depict enhanced cellular morphology, indicating that the precise water delivery system of drip irrigation optimally supports root expansion and nutrient uptake. In contrast, roots exposed to surface irrigation displayed comparatively smaller dimensions and less defined structures. This visual evidence underscores the advantages of drip irrigation in promoting better root health, development and overall plant vigour, thereby contributing to improved crop performance in terms of drought resilience and yield potential (13, 14). Research suggested xylem vessels, which accounts for the pigeon peas' cautious early growth. Chickpea and cowpea showed moderate xylem passage per root indicating that they are capable of absorbing water moderately and are well-equipped for regular drought episodes (15).

Such findings emphasize the importance of efficient irrigation practices in enhancing agricultural productivity, particularly in resource-limited environments where water management is critical for sustaining crop growth and ensuring food security. The observable differences in root structure illustrated by the SEM analysis highlight the need for further exploration into irrigation methods that maximize plant health and productivity for various legume crops (16).

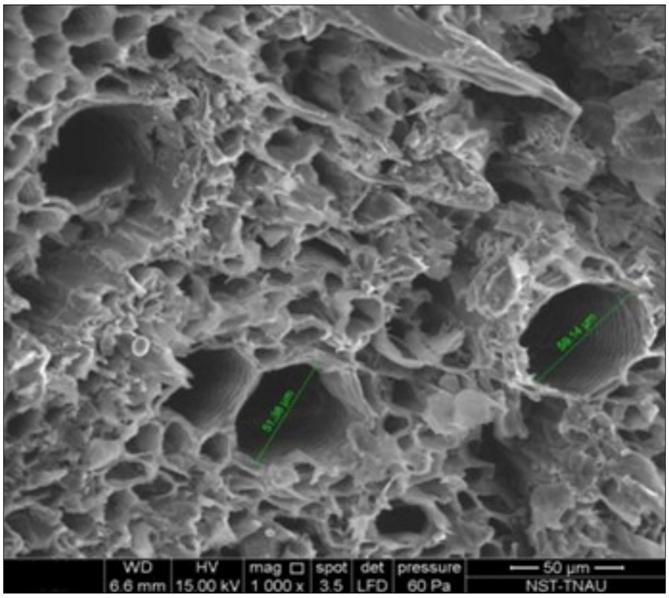
Notably, studies have demonstrated that pigeon peas can exhibit bimodal distributions in vessel diameter, indicative of a response strategy to contrasting environmental conditions.

Table 1. Anatomical investigations by SEM on pigeon pea under drip fertigation and surface irrigation

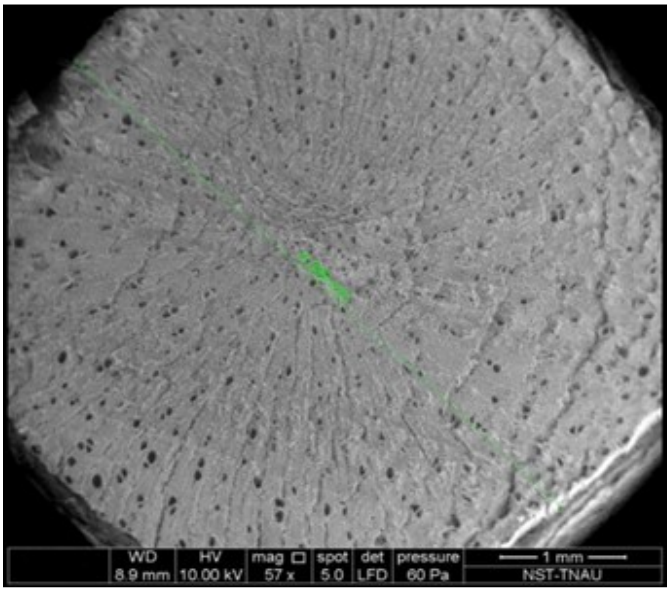
S. No	Particulars	Surface irrigation at conventional fertilizer and (IW/CPE 0.6)	Drip irrigation at 100 % RDF through WSF and 100 % WRc
	ROOTS		
1.	Whole diameter of roots (mm)	5.189	5.395
2.	Number of xylem cells in the root	264	332
3.	Avg. diameter of xylem cell (µm)	55.26	68.31
	STEM		
1.	The whole diameter of the stem (mm)	5.809	6.591
2.	No. of xylem cells in stem	256	304
3.	Avg. diameter of xylem cell (µm)	62.95	79.41



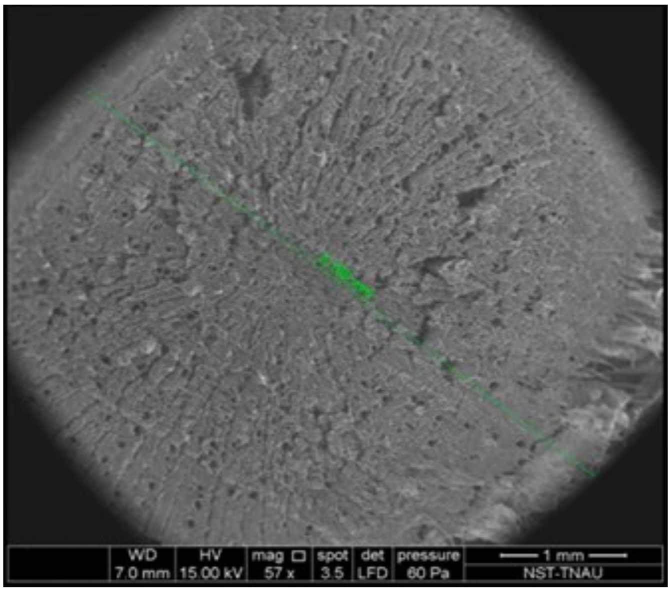
Diameter of xylem cell in root at drip irrigation



Diameter of xylem cell in root at Surface irrigation



The whole diameter of the root at drip irrigation



The whole diameter of the root at surface irrigation

Fig. 1. SEM images of pigeon pea root xylem under drip irrigation and surface irrigation.

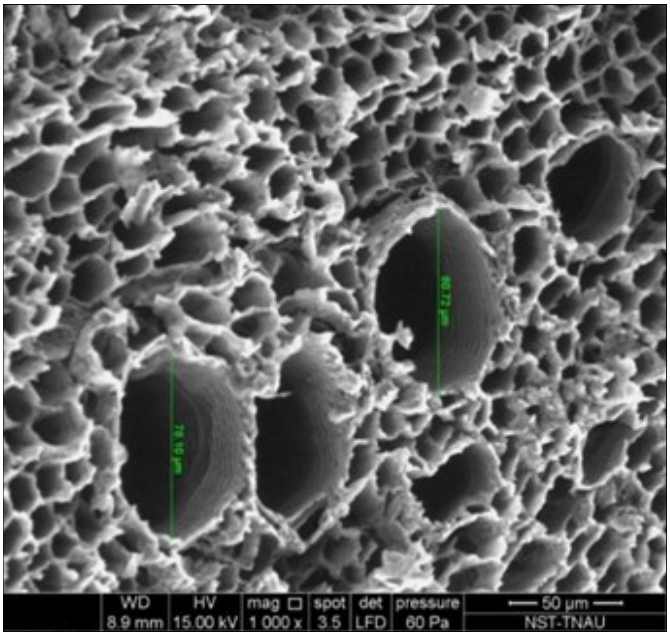
Under favorable conditions, larger vessels are favored; however, when conditions become more arid, the selection may shift towards smaller vessels that are more resistant to embolism, thereby ensuring stable water transport capabilities even under suboptimal circumstances.

Additionally, climatic factors, such as mean annual precipitation and temperature, significantly influence vessel diameter and distribution patterns. Elevated precipitation levels contribute to an increase in average vessel size, which potentially enhances overall water transport efficiency. However, this relationship exhibits a complex interplay with atmospheric conditions, wherein excessively humid conditions may lead to negative pressure within the xylem, heightening susceptibility to cavitation (17).

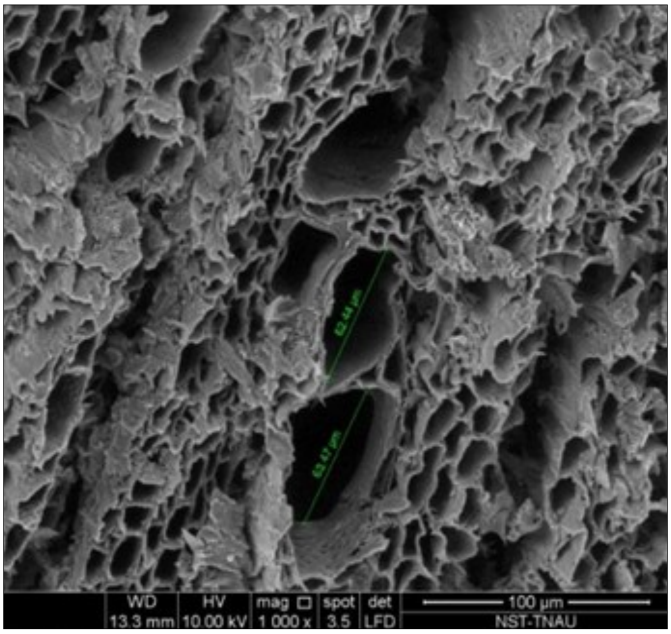
Moreover, xylem vessel size impacts not only water transport but also the physiological balance of nutrients, all critical for the equilibrated growth stem xylem diameter of pigeon pea shown in (Fig. 2). Studies indicated that plants with optimized hydraulic designs experience less water stress, which in turn fosters better carbon assimilation and root development, ultimately aiding in nutrient acquisition under drip irrigation systems (18).

Studies have shown that because plants that receive enough moisture can prioritize effective water transport pathways, this type of localized watering can encourage the growth of larger xylem vessels. (19). For instance, research on grapevines has demonstrated that plants under drip irrigation systems exhibited larger vessel diameters compared to those under water stress conditions due to other irrigation methods (20). The increase in vessel size is associated with enhanced hydraulic conductivity, allowing for more efficient water transport to leaves and supporting higher photosynthetic rates and studies have shown vessel diameter, hydraulic conductivity and vulnerability to cavitation were in the order of deep root > shallow root > branch (21).

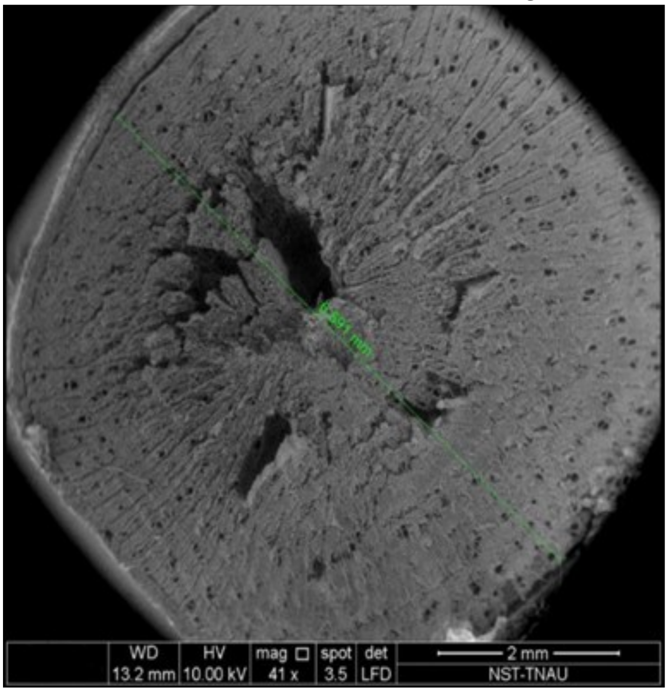
Drip irrigation typically leads to the development of larger xylem vessels. When water is consistently available, plants can invest in larger conduits, facilitating efficient water movement. In



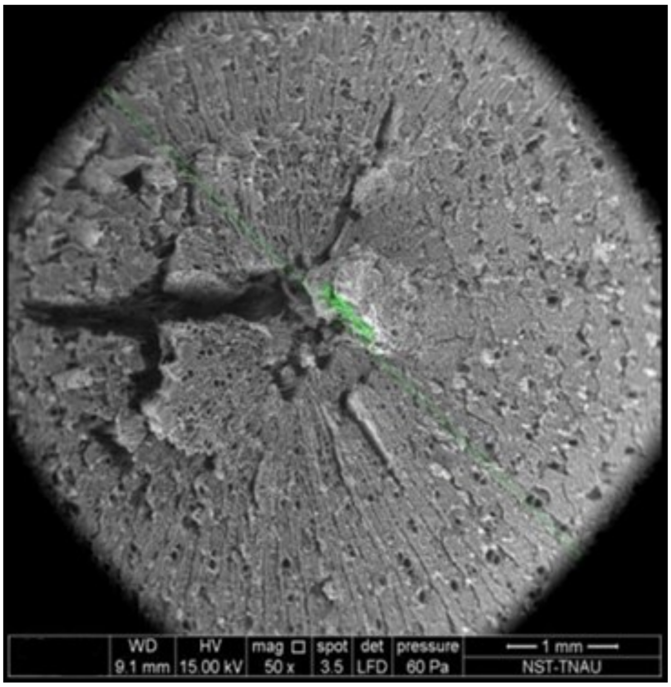
Diameter of xylem cell in the stem at drip irrigation



Diameter of xylem cell in the stem at Surface irrigation



The whole diameter of the stem at drip irrigation



The whole diameter of the root at surface irrigation

Fig. 2. SEM images of pigeon pea stem xylem under drip irrigation and surface irrigation.

essence, an understanding of the anatomical cross-sections of pigeon pea roots reveals critical insights into how irrigation methods influence xylem vessel morphology. The capacity of pigeon pea to adjust its xylem architecture in response to water availability, coupled with inherent genetic adaptability, positions it as an important crop for sustainable agricultural practices, particularly in drought-prone environments (22).

The implications of these findings underscore the necessity for continued research (10). This not only advances our scientific understanding but provides essential guidance for developing agricultural strategies that optimize water use efficiency and crop yield.

Larger vessels are beneficial for maintaining higher rates of water transport, especially during peak transpiration periods. They also reduce the risk of embolism, the blockage of vessels caused by air bubbles, which is critical during periods of fluctuating water availability, a common challenge in drip irrigation systems.

This method usually results in an uneven distribution of moisture, leading to variable xylem vessel response depending on the proximity to water sources. Plants closer to the furrow may develop adapted xylem dimensions in response to increased moisture, while those farther away may exhibit reduced vessel size due to water stress. As with flood irrigation, prolonged stress leads to smaller vessel sizes in furrow-irrigated plants, which is an adaptive trait to minimize hydraulic failure during dry periods (22).

Understanding the adaptations of xylem vessels is crucial for optimizing irrigation techniques based on specific crop needs. Drip irrigation not only enhances the growth of large vessels conducive to efficient water transport but also crucially supports hydraulic safety via structural adaptations in response to variable water availability. The formation of larger vessels increases the capacity to transport water under optimal conditions, as the research indicates a positive correlation between vessel size and overall hydraulic efficiency. In regions subjected to variable climatic conditions, drip-irrigated plants can maintain robust growth and yield, even during drought periods, by adjusting their xylem structures to ensure optimal hydration and nutrient transport.

Conclusion

In conclusion, the adaptability of pigeon pea's xylem vessel size under different irrigation regimes in three varieties of pigeon pea offers a compelling avenue for further investigation in drip irrigation, potentially leading to improved agricultural practices that enhance water utilization and nutrient uptake while maintaining productivity in adverse climatic conditions. The implications of irrigation techniques on xylem vessel size are significant, influencing not only the immediate water transport efficiency but also the long-term resilience of plants to environmental stresses. Drip irrigation stands out as a beneficial method for enhancing xylem vessel size and overall hydraulic efficiency, positioning it favorably against traditional methods like flood, sprinkler, or furrow irrigation. These findings underscore the necessity to tailor irrigation strategies to specific environmental conditions and plant needs to optimize water use efficiency and crop productivity, particularly as climate variability continues to challenge agricultural practices globally. This research in this field is imperative, given the water sources and the need for sustainable food production systems worldwide.

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Authors' contributions

JR carried out conceptualization, investigation and original drafts preparation. VN carried out conceptualization, data curation and investigation. VP carried out supervision, formal analysis, review editing and plagiarism. MS and ASB carried out review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical issues: None

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