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Influence of Temperature on Xylem Nutrient Transport in Plants

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Abstract - The current study investigates how ambient temperature affects streaming potential-induced electrical energy generation triggered by nutrient flow in the stem xylem. During the experiment, the streaming potential of *Brassica juncea* is measured at various atmospheric temperatures, and the pressure gradient is computed for numerical simulations. It has been found that as atmospheric temperature rises, the increase in transpiration pull augments both axial and radial flow velocities. This enhances the flow loading at the intersection of the stem xylem core region and the porous pitted wall. Consequently, as atmospheric temperature increases, the mechanical stress inside the pitted porous wall also rises. Furthermore, due to convection-driven ionic transport, it becomes apparent that the magnitude of the induced potential at the bottom side of the stem xylem increases with rising atmospheric temperature. Additionally, owing to the ion-partitioning effect caused by differences in electrical permittivity, the concentration of K⁺ appears to be substantially lower in the pitted porous wall. As atmospheric temperature rises, the streaming electric field strengthens, enhancing both electrical and hydraulic power. Interestingly, atmospheric temperature has almost no influence on energy conversion efficiency. The insights drawn from this study contribute to a better understanding of the impact of atmospheric temperature on the development of green energy generation devices with high power densities.

Keywords: Xylem, streaming potential, atmospheric temperature, hydraulic energy, electrical energy.

1. Introduction

The ongoing global energy crisis and environmental pollution attract the research community toward renewable energy solutions [1], [2]. With recent advancements in micro/nanofluidic technologies, several self-sustained energy-harvesting devices have been fabricated to fulfil small-scale energy needs. Although these devices have emerged as very promising renewable sources, many still require some form of external energy input for functioning. In this regard, plants can serve as a vital source of electricity due to the pressure-driven flow of ionic nutrient solutions through the xylem vessels [3], [4], [5].

Previous experiments on transport phenomena in plants have revealed that nutrient flow through xylem vessels occurs due to the osmotic pressure of the root and the transpiration pull from the leaf [6], [7]. The leaf transpiration pulls increases with rising atmospheric temperature [8]. Furthermore, the walls of xylem vessels are composed of cellulose, which contains negatively charged carboxylic groups. The presence of these carboxylic groups imparts a negative zeta potential to the xylem vessels [9], [10]. Consequently, the flow of ionic nutrient solution over the negatively charged walls of xylem vessels generates a streaming current, which can be extracted as electrical energy. It has been reported that streaming potential-mediated energy generation in micro/nanofluidic confinements is significantly affected by temperature gradients [11], [12]. However, the effect of ambient temperature on streaming potential-driven energy generation via xylem flow has yet to be examined. Therefore, the objective of the current work is to investigate this phenomenon.

2. Experimental and Mathematical modelling

We depict a typical plant and the flow of nutrient solutions (water + ions: Ca^{2+} , K^+ , Fe^{2+} , Zn^{2+} , Cl^- , SO_4^{2-}) through the stem xylem vessel in Fig. 1(a). During nutrient flow in the stem xylem, the accumulation of counter-ions due to the streaming electric field is generated and can be extracted as electrical energy, as illustrated in Fig. 1(a). Furthermore, atmospheric pressure significantly modulates this process by influencing the transpiration rate at the leaf surface. Hence, the flow of nutrient solutions in plants under different climatic conditions can serve as a source of clean, renewable energy. Inspired by

this phenomenon, we investigate streaming potential-mediated energy generation in plants at different atmospheric temperatures throughout the day.



Fig. 1: (a) A typical plant with the vascular bundle and zoomed-in view of the transport of ionic nutrient solution through the stem xylem vessel, (b) computation domain of the stem xylem vessel along with the pitted wall and mesh structure.

 Table 1: Variation of atmospheric temperature, root temperature, stem xylem wall temperature, streaming potential, and pressure gradient over time during the experiment.

Time		
8.00 AM	10.00 AM	12.00 PM
22.5±0.15	23.7±0.44	24.3±0.78
18.3±0.50	18.8±0.3	18.8±0.67
19.55±0.72	20.3±0.53	21.3±0.85
0.0659 ± 0.0091	0.0691 ± 0.006	0.0865±0.0039
1061696±96067.39	1112559.75±87499.78	1286100±61947.89
	8.00 AM 22.5±0.15 18.3±0.50 19.55±0.72 0.0659±0.0091 1061696±96067.39	Time 8.00 AM 10.00 AM 22.5±0.15 23.7±0.44 18.3±0.50 18.8±0.3 19.55±0.72 20.3±0.53 0.0659±0.0091 0.0691±0.006 1061696±96067.39 1112559.75±87499.78

2.1. Experimental Analysis

We consider a 50-day-old *Brassica juncea* (ICAR-IARI, Regional Station, Karnal, Haryana) grown on the Indian Institute of Technology, Guwahati, India campus in December 2024. The stem xylem and root temperatures are measured using a thermocouple connected to a digital multimeter (Fluke[®]). Furthermore, the streaming potential is estimated by inserting two brass electrodes at two different locations, 60 cm apart along the plant body. The readings are taken with the help of a digital multimeter (Fluke), connecting its two terminals to the tips of the electrodes, following the method used by Guha et al. [13]. The streaming potential values are recorded at 2-hour intervals from 8 AM to 12 PM. These data are then used to evaluate the pressure drop inside the plant using the formula [13]: $\Delta p = \sigma \mu V_s / \epsilon \epsilon_0 \zeta$; where Δp , σV_s , ϵ_0 , ϵ_r , and ζ are the pressure drop, electrical conductivity (= 0.1 S/m) [13], dynamic viscosity (= 0.001 Pa-s), measured streaming potential, electrical permittivity of free space (= 8.85×10^{-12} F/m), relative electrical permittivity of nutrient solution (= 80) and zeta potential of stem xylem wall (= -15 mV), respectively. The average readings of root temperature, stem xylem wall temperature, streaming potential, pressure drop, and pressure gradient at each atmospheric temperature are provided in Table 1.

2.2. Mathematical modelling and numerical framework

We develop a two-dimensional computational model of a stem xylem vessel between two reservoirs, namely the rootside and shoot-side reservoirs, as illustrated in Fig. 2(b), to mimic realistic transport in plants. Considering the steady, laminar, and incompressible flow of ionic nutrient solutions in the stem xylem vessel, the governing equations describing the potential, flow, ionic concentration, temperature, and deformation fields can be expressed as follows:

For void region of stem xylem:

Poisson equation of electrical-double layer (EDL) [14]:

$$\nabla \cdot (\varepsilon_0 \varepsilon_c \nabla \psi) = -F \sum_{i=1}^6 Z_i c_i$$
⁽¹⁾

Here, ϵ_0 and ϵ_e are the dielectric permittivity of free space and relative permittivity of the stem xylem vessel, respectively, ψ is the electric potential, F is Faraday constant, z_i is the ion valence, c_i is the concentration of the ith ionic species.

Nernst-Planck equation of ionic concentration field [14]:

$$\nabla \cdot \left(\mathbf{j}_{i}\right) = \nabla \cdot \left(-\mathbf{D}_{i} \nabla \mathbf{c}_{i} - \mathbf{z}_{i} \frac{\mathbf{D}_{i}}{\mathbf{RT}} \mathbf{F} \mathbf{c}_{i} \nabla \boldsymbol{\Psi} + \mathbf{u} \mathbf{c}_{i}\right) = 0$$
⁽²⁾

Here, D_i , **R**, **u** and **T** denotes the diffusion coefficient of ith ionic species, universal gas constant, velocity vector and absolute temperature, respectively. Moreover, the flow field is governed by the following continuity and momentum equations [14]:

$$\nabla \cdot \mathbf{u} = 0 \tag{3}$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \left(F \sum_{i=1}^6 z_i c_i\right) (-\nabla \psi)$$
(4)

Where, ρ and p are the density of the nutrient solution and pressure inside the stem xylem vessel, μ [= 2.761×10⁻⁶exp(1713/T)] Pa-s is the temperature-dependent dynamic viscosity of the nutrient solution [15]. For the temperature field, the energy equation is presented below:

$$\rho C_{p} \mathbf{u} \nabla T + \nabla \cdot (-k \nabla T) = 0 \tag{5}$$

Where, k (= 0.61+0.0012(T-298) W/m-K [15] is the temperature-dependent thermal conductivity and C_p (= 4200 J/Kg-K) is the specific heat capacity.

For a porous potted wall of stem xylem:

Poisson equation of electrical double layer (EDL):

$$\nabla \cdot (\varepsilon_0 \varepsilon_p \nabla \psi) = -F \sum_{i=1}^{\circ} z_i c_i - \rho_{\text{fixed}}$$
(6)

Here, ε_p (= 0.053) and ρ_{fixed} (= $\sim \varepsilon_0 \varepsilon_c (\zeta/l_{\lambda}^2)$ =-1062 C/m³) are the relative permittivity of the pitted wall and fixed space charge density of the same, estimated based on -15 mV surface potential (ζ) [16] and ~100 nm EDL thickness (l_{λ}) around the pitted pores of the pitted wall.

Nernst-Planck equation of ionic concentration field:

$$\nabla \cdot \left(\mathbf{j}_{p,i}\right) = \nabla \cdot \left(-D_{p,i}\nabla c_{i} - z_{i}\frac{D_{i}}{RT}Fc_{i}\nabla\psi + \mathbf{u}_{p}c_{i}\right) = 0$$
(7)

Here, $D_{p,i}$ is the equivalent ionic diffusion coefficient in porous media using the Millington and Quirk model as $D_{p,i} = D_i (\epsilon^{4/3})$ [17] and $D_i = D_{i,0} (1+0.03039(T-298))$ m²/s [15]; $D_{i,0} = 0.793$, 1.96, 0.715, 0.719, 1.9, 1.07×10^{-9} m²/s for Ca²⁺, K⁺, Fe²⁺, Zn ²⁺, Cl⁻, SO₄⁻², respectively [17]; \mathbf{u}_p is the Darcy velocity field. Similarly, the flow field equation is represented as:

$$\nabla \cdot \mathbf{u}_{\mathbf{p}} = 0 \tag{8}$$

$$\left(\rho/\epsilon^{2}\right)\left(\mathbf{u}_{p}\cdot\nabla\right)\mathbf{u}_{p} = -\nabla p + \mu\nabla^{2}\mathbf{u}_{p} - \left(\kappa\mathbf{u}_{p}/\mu\right) + \left(F\sum_{i=1}^{6}z_{i}c_{i}\right)\left(-\nabla\psi\right)$$

$$\tag{9}$$

Where, κ is the permeability of the porous pitted wall. In the same way, the energy equation is written below:

 $\rho C_{p} \mathbf{u}_{p} \nabla T + \nabla \cdot \left(- \left(k \varepsilon + k_{p} \left(1 - \varepsilon \right) \right) \nabla T \right) = 0$

Where, k_p is the thermal conductivity of the porous solid and is taken as 0.3 W/m-K [18] and ϵ is the porosity of the pitted wall.

For the deformation field (*V_s*), the following equation has been solved numerically [17]: $\nabla(FS)^T = 0$

Where, $\mathbf{F} (=\mathbf{I} + \nabla V_S)$ and $\mathbf{S} (2\mu_L \bar{\boldsymbol{\varepsilon}} + \lambda_L tr(\bar{\boldsymbol{\varepsilon}})\mathbf{I})$ are the displacement gradient and second-Piola-Kirchhoff stress. Here, $\bar{\boldsymbol{\varepsilon}} = 0.5(\boldsymbol{F}(\boldsymbol{F})^T - \boldsymbol{I})$ denotes the Lagrange-Green strain. Moreover, the first and second Lame parameters in terms of modulus of elasticity ($E_p = 2500$ MPa) and Poisson's ratio ($v_p = 0.35$) is given as $\lambda_L = v_p E_p / (1 + v_p)(2v_p - 1)$, $\mu_L = E_p / 2(1 + v_p)$. In addition, the Cauchy stress tensor ($\bar{\boldsymbol{\sigma}}$) is represented as $\bar{\boldsymbol{\sigma}} = \frac{1}{J} (\boldsymbol{FS}(\boldsymbol{F})^T)$; here, the Jacobian of \boldsymbol{F} is represented by J. The interfacial (Γ) condition is given by $\bar{\boldsymbol{\sigma}} \cdot \boldsymbol{n}_{p,\Gamma} = -(p\boldsymbol{I} + \mu \nabla \boldsymbol{u}) \cdot \boldsymbol{n}_{f,\Gamma}$. The porous domain is fixed at the upper and lower ends, and free at the wall.

The aforementioned equations have been solved by implementing the following boundary conditions:

or potential field: at the stem xylem wall $\psi = -15$ mV, at the centerline, $\partial \psi / \partial r = 0$, at the reservoirs' side walls, $\psi = 0$. For ionic concentration field: near the root side reservoir, the concentration of calcium, potassium, ferrous, zinc, chloride, and sulfate ions are $c_{Ca^{2+}} = 0.0625 \text{ mol/m}^3$, $c_{k^+} = 0.0256 \text{ mol/m}^3$, $c_{Re^{2+}} = 0.06858 \text{ mol/m}^3$, $c_{Za^{2+}} = 0.06057 \text{ mol/m}^3$, $c_{CT} = 0.01 \text{ mol/m}^3$, $c_{SO^{2-}} = 0.1 \text{ mol/m}^3$, respectively [19]. From the study of Khan et al. [19], we have found that the gradient of some ionic species occurs between the root and the shoot of the plants. Therefore, we have taken the concentration of the shoot side reservoir as, $c_{c_{a^{2+}}} = 0.0625 + (7.5 \times 10^{-2}) \times L \text{ mol/m}^3$ $c_{k^{2}} = 0.0256 + (-1.1076 \times 10^{-6}) \times L \text{ mol/m}^{3}, c_{re^{2+}} = 0.06858 + (3.58 \times 10^{-2}) \times L \text{ mol/m}^{3}, c_{zn^{2+}} = 0.06057 \text{ mol/m}^{3}, c_{cn^{-}} = 0.01 \text{ mol/m}^{3}, \text{ and } c_{so^{2-}} = 0.1 \text{ mol/m}^{3}.$ Here, L is the length of the stem xylem vessel, which is considered as 55 μ m. At the centerline, $\partial c_i / \partial r = 0$, at the stem xylem wall, $\nabla \cdot (\mathbf{j}_i) = 0$. Further, the ionic concentration field at the interface is affected by the electric permittivity difference, and hence, the ion partitioning effect is taken as $c_{i,p} / c_i = \exp(-\Delta w_i / k_b T)$ and $\Delta w_i = [(z_i e)/8\epsilon_0 \pi r_i]((1/\epsilon_p) - (1/\epsilon_c))$ [14]. The value of the ionic radius is given as $r_i = 4.12, 3.31, 4.30, 2.15, 3.32, 3.79$ Å for Ca²⁺, K⁺, Fe²⁺, Zn²⁺, Cl⁻, SO₄⁻², respectively [20]. For the flow field, at the stem xylem wall $\mathbf{u} = 0$, at inlet $P = P_{in}$, at the outlet $P = P_{atm}$ and at the stem xylem wall, $p = (0.04 \times z)$ MPa. For energy equation: at the inlet, $T = T_r$, at the xylem wall, $T = T_w$ [refer to Table 1], at the remaining walls of the reservoirs, $\mathbf{n} \cdot (-(k\epsilon + k_p(1-\epsilon))\nabla T) = 0$ or $\mathbf{n} \cdot (-k_{eff}\nabla T) = 0$. We estimate the streaming potential by calculating the streaming electric field using the expression of streaming current (Is) and conduction current (I_{Conduction}). Remarkably, the external electric field does not exist in the stem xylem; thus, to maintain electro-neutrality, I_s should be equal to $I_{Conduction}$, i.e., $I_s + I_{Conduction} = 0$. In the mathematical form, the streaming current can be expressed as [13]:

$$I_s = F \int (uc_i dr) w$$

(12)

(10)

(11)

Here, w = periphery of the stem xylem vessel. The conduction current can be expressed in the following form [13]:

$$I_{\text{Conduction}} = -E_{s}F\left(\int F\left(\sum \frac{z_{i}D_{i}}{RT}c_{i}\right)dr\right)w$$
(13)

Here, E_s is the streaming electric field and can be expressed in terms of the streaming potential as $V_s = E_s L$. Further, the electrical energy conversion efficiency obtained from the pressure-driven flow of nutrient solution can be estimated by calculating the electrical power (I_sV_s) and hydraulic power ($Q\Delta p$). Here, Δp is the pressure difference across the stem xylem vessel and Q is the corresponding flow rate, $Q = \pi/4D^2u_{zAverage}$. Here, $u_{zAverage}$ is the average axial velocity. Hence, the mathematical form of energy conversion efficiency is written as follows [13]:

$$\eta = \frac{I_s V_s}{Q \Delta p} \tag{14}$$

We used COMSOL Multiphysics software to solve the highly coupled aforementioned equations with a triangular non-uniform mesh, as shown in Fig. 1(b). To convert the differential equations into a system of linear equations, a linear shape function is used for the velocity, temperature, and pressure fields, whereas a quadratic shape function is applied to the EDL potential field, concentration field, and deformation field. To optimise computational cost, we employed a segregated solver to compute all variables step-by-step in an iterative manner. Based on the grid independence test, the number of elements was set to 23,895.

3. Results and discussions



Fig. 2: (a) Axial velocity contours and radial flow velocity vectors in the porous pitted wall at different atmospheric temperatures. (b) Internal stress distribution within the porous pitted wall along with the load at the interface, for different atmospheric temperatures.

In this study, we investigate the effect of atmospheric temperature on streaming potential-mediated electrical energy generation in plants, attributed to the transport of nutrient solution through the stem xylem vessels. We first experimentally measure the streaming potential of *Brassica juncea* at different atmospheric temperatures throughout the day. This allows us to calculate the pressure gradient inside the stem xylem vessels. The pressure gradient data is then incorporated into numerical simulations to systematically analyze the flow field, concentration field, outward radial velocity, mechanical stress, load, streaming electric field, electrical power, hydraulic power, and energy conversion efficiency under different atmospheric temperature conditions (22.4° C, 23.7° C, and 24.3° C). We consider the porosity of the stem xylem vessel to be 0.0531 and the diameter of the stem xylem wall pit to be 2.6 µm [21]. The permeability of the porous wall of the stem xylem vessel is calculated as 1.27×10^{-17} m² using the Kozeny–Carman equation [22] for cylindrical pores.

The axial velocity contours and radial flow velocity vector lines at various ambient temperatures are shown in Fig. 2(a). As the atmospheric temperature increases, both axial and radial velocities are observed to rise. This phenomenon can be attributed to the increase in atmospheric vapour pressure due to higher temperatures, which enhances the evaporation rate at the leaf surface [8]. Consequently, the stronger transpiration pull leads to an increase in both axial and radial flow velocities inside the stem xylem.

Furthermore, the flow loading at the interface also intensifies due to the temperature-induced enhancement of the flow field, as illustrated in Fig. 2(b). As a result, the porous pitted wall experiences an increase in mechanical stress intensity with rising atmospheric temperature, as shown in Fig. 2(b). Additionally, the pressure gradient from the base to the top of the stem xylem leads to a reduction in both flow loading and mechanical stress in the upward direction.



Fig. 3: (a) Contours of the induced potential field along with axial electric field lines. (b) K^+ concentration field at different atmospheric temperatures.

Figure 3(a) illustrates the contours of the induced potential and axial electric field lines in the stem xylem and its pitted wall at different atmospheric temperatures. The results indicate that the axial electric field is induced in the direction opposite to the flow due to the generation of streaming current by flow-driven ionic flux in the axial direction. As atmospheric temperature increases, the convective ionic flux also increases, leading to a higher induced potential magnitude at the bottom of the stem xylem.



Fig. 4: Variation in (a) axial streaming electric field (b) electric

power, (c) hydraulic power, and (d) energy conversion efficiency in

response to different atmospheric temperatures.



different atmospheric temperatures. The comparison is also shown with the results of Xue et al.[23] and Zhou et al.[24].

Further, the K⁺ concentration field is presented in Fig. 3(b) in terms of pK^+ (= $-log_{10}c_{K^+}$). It is observed that K⁺ concentration significantly decreases inside the pitted wall region. This reduction is attributed to the lower electrical permittivity inside the porous pitted wall, which leads to higher Born energy, making it energetically unfavourable for K⁺ ions to remain in this region. In contrast, the higher electrical permittivity of the liquid in the void region results in lower Born energy, creating a more favourable environment for K⁺ ion migration. Consequently, K⁺ ions preferentially move toward the low-energy void region, leading to a consistently lower K⁺ concentration inside the porous pitted wall across all atmospheric temperatures.

Furthermore, the effect of atmospheric temperature on energy generation characteristics is illustrated in Figs. 4(a)–(d). It is observed that the intensity of the streaming electric field increases with rising atmospheric temperatures [Fig. 4(a)]. This is attributed to the enhanced convective ionic flux, driven by the higher throughput in the stem xylem vessels at elevated temperatures, as previously noted in Fig. 2(a). The stronger induced electric potential at higher temperatures [Fig. 4(b)] further contributes to an increase in electrical energy production. Additionally, hydraulic power is found to increase with atmospheric temperature [Fig. 4(c)], primarily due to the enhanced transpiration pull at the leaf surface, consistent with the observations from Fig. 2(a). Interestingly, energy conversion efficiency remains nearly unaffected by changes in atmospheric temperature [Fig. 4(d)]. In summary, these findings highlight the significant role of atmospheric temperature in streaming potential-mediated energy harvesting from plants, influencing both electric potential generation and hydraulic power, while having minimal impact on energy conversion efficiency.

We have compared the resulting electrical power density with various evaporation-based energy generation strategies. Figure 5 illustrates the variation of electrical power density at different atmospheric temperatures. It is observed that as the ambient temperature increases, the power density also rises, which correlates with the increase in electrical power [see Fig. 4(b)]. Interestingly, the power density in our study surpasses that of evaporation-based energy generation reported by Xue et al. [23] and Zhou et al. [24]. This highlights the effectiveness of stem xylem-driven nutrient flow in achieving higher power density compared to conventional evaporation-based approaches. Thus, our findings demonstrate that streaming potential-mediated energy harvesting from plants offers a promising avenue for efficient bioelectric energy generation with superior power density.

4. Conclusion

The present study investigates nutrient transport and energy generation in stem xylem vessels under varying atmospheric temperatures. We first experimentally measure the streaming potential of Brassica juncea, which is then used to estimate the pressure gradient inside the stem xylem vessels. These pressure gradient data are incorporated into two-dimensional numerical simulations to analyse the axial and radial flow fields, internal mechanical stress, flow load, nutrient concentration field, streaming electric field, electrical power, hydraulic power, and energy conversion efficiency. Our findings indicate that streaming potential increases with rising atmospheric temperature, leading to an enhanced pressure gradient inside the stem xylem vessels. This, in turn, results in higher axial and radial flow velocities due to stronger advection forces induced by leaf transpiration pull. As a consequence of increased flow velocity, the internal mechanical stress and flow load at the interface between the porous pitted wall and the stem xylem core region also rise at higher temperatures. Additionally, the contrast in electrical permittivity between the nutrient solution and the stem xylem vessel walls results in a lower concentration of nutrient ions within the porous pitted wall. The higher convective flux within the stem xylem further strengthens the streaming electric field, particularly near the bottom region of the stem xylem vessel, where the magnitude of the induced potential is significantly higher. A stronger electric field within the stem xylem at elevated temperatures facilitates greater electrical power generation. While energy conversion efficiency remains largely unaffected by atmospheric temperature, electrical power density increases as temperature rises. Notably, the power density estimated in this study exceeds previously reported values from evaporation-driven energy generation techniques. Thus, our findings suggest that plants growing in tropical and subtropical climates can serve as a sustainable source of bioelectric energy, leveraging streaming potentialinduced power generation within their stem xylem vessels.

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