An Instrumentation-based Experimental Study on Biomechanical Property of Plant Tendril – A Probable Application in Bioinspired Technology

Shibsankar Roy[1*], Barnini Bhattacharya[2]

[1]Guest Teacher, Department of Biochemistry and Biophysics, University of Kalyani

[2]Teaching Assistant, Department of Medical Laboratory Technology, Swami Vivekananda University, Barrackpore

*Corresponding Author

Abstract

Plant tendrils are specialized spring-like coiled structures found in climber plants that provide them support and strength. The pattern of coiling includes both, clockwise and anticlockwise helix. Due to its characteristic spring-like structure, identification of its mechanical strength is considered to be an important area of research, in recent times. A few works have focused on studying the tensile strength and other mechanical properties of plant tendrils in controlled conditions. However, because tendrils are relatively soft-tissue structures, proper mounting of tendrils for use in biomechanical experimentation remains a challenging area of research. In view of this, in the present study, a specialized Tendril Strain Quantification instrument, based on principles of Hook's Law was developed indigenously, to study the biomechanical property of plant tendrils. The mechanical property of the tendrils was quantitatively studied in terms of mechanical strain, which is the relative lengthwise deformation in structure, compared to a reference positional configuration following an applied load. From the study it was found that tendrils with both clockwise and anticlockwise coiling (bi-directionally helical) exhibited better mechanical strength in comparison to single coiled tendrils. Thus, the study indicated that tendrils with bidirectional coiling act as better springs in comparison to that of single coiled tendrils. The findings may be used in future, for development of bioinspired technology based on plant tendrils.

Keywords: Hook's Law, Tendrils, Mechanical Strength, Bioinspired technology

I. INTRODUCTION

Climbing and creeping plants have evolved unique evolutionary strategies to optimize light interception and space acquisition (natural sensory cues) through development of specialized and sensitive lateral organs known as tendrils. In the pioneering studies conducted by the biophysicist Acharya Jagadish Chandra Bose it has been already reported that the tendrils, the specialized sensitive organs of the creeping plants exhibit alteration in stimulus sensitivity depending on several factors like seasonal variation, age of the plant, mode of stimulus application (like bilateral or unilateral) and so on [1]. Recent studies have shown that in order to navigate vertical spaces against vectorial natural factors like gravity, the tendrils rely on specialized morphological adaptations known as tendrils. Tendrils are specialized, filiform appendages that exhibit high sensitivity to mechanical contact [2]. Structurally, these helical organs are heavily reinforced with sclerenchyma, a specialized plant tissue characterized by thickened, lignified secondary cell walls that provide exceptional mechanical rigidity and tensile resistance.

The structural utility of the tendril operates through a multi-phase mechanical process. Upon encountering a physical substrate, thigmomorphogenetic signaling triggers differential growth rates across the organ, causing the tendril to anchor by coiling securely around the support [3]. Following this initial attachment, the unattached intermediate region of the tendril undergoes a secondary developmental phase characterized by additional coiling along its longitudinal axis. This process, often referred to as tendril perversion, creates two opposing helical domains separated by a distinct twist, commonly termed as a perversion stretch [4]. This structural modification results in a dramatic shortening of the tendril length, effectively pulling the main plant stem closer to the supporting substrate.

From a biomechanical perspective, this helical conformation functions as a biological spring. Rather than acting as a rigid tether, the coiled tendril behaves as a low-stiffness spring under low tensile loads, allowing the plant to flex dynamically in response to transient environmental forces such as wind or rain. Under high displacement or strong loading conditions, however, the spring structurally stiffens, displaying a unique asymmetric behavior that prevents root detachment or stem breakage. Consequently, the study of tendril biomechanics—specifically parameters such as tensile strength, structural elasticity, and energy dissipation—has attracted significant interest across the fields of functional plant biology, biomimetics, and materials science.

Despite the growing body of literature characterizing these macroscopic properties, a significant methodological challenge limits the accuracy of current empirical data. Preliminary investigations have traditionally evaluated tendril tensile strength under idealized, controlled laboratory settings using standard universal testing machines. However, a critical research gap persists regarding the secure, non-destructive anchoring of these specimens during mechanical testing. Because dehydrated or fresh tendrils are delicate, highly irregular, and morphologically prone to localized crushing or slipping within standard mechanical grips, traditional tensile testing configurations frequently introduce structural artifacts. Mechanical stress concentrations at the rigid clamping interface often precipitate premature specimen failure, thereby resulting in errors during measurements of the material's true ultimate tensile strength and elastic modulus.

In the mentioned backdrop, the present study aimed at studying the biomechanical property of the plant tendril under several helical combinations. The biomechanical property of the tendrils has been assessed in terms of the mechanical strength. In order to quantitatively study the mechanical property, a customized tendril strain quantification instrument was developed that allowed secure mounting of the tendrils for use in experimentation. The study findings may prove to be plausible for development of bioinspired technology, in the near future.

II. LITERATURE REVIEW

In recent times several research works have been performed on development of innovative technologies based on biomechanics of plant tendrils. A recent work has reported development of sensors based on plant-related adhesion mechanism of tendrils [5]. Another recent study has developed a low-cost and environmentally friendly soft actuator for the widespread application of thermoplastic films based on tendril of plants [6]. Another recent work has focused on development of a liquid crystal elastomer spiral fibers using a simplified and low-cost approach based on design principles of a natural plant tendril [7]. A recent review has highlighted the robust material properties and thought-provoking functionalities of plant tendrils, such as actuation properties, weight bearing abilities and etc. [8]. In another recent study a biomimetic piezoelectric vibration sensor inspired by the spiral structure of plant tendrils has been developed by a group of researchers [9]. Another similar work has reported the development of a bio-inspired adhesive interface based on the multi-scale adhesion mechanism of a plant tendril [10].

III. METHODOLOGY

Selection of Model Plant

The plant *M. pendula* is a slender and climbing plant. It has specialized slender spirally coiling sensitive organ called tendrils that serves to attach the climbing plant to its support (Mustaqim and Putra 2020). The present study was focused on the specialized tendril organ of the plant (Fig. 1).

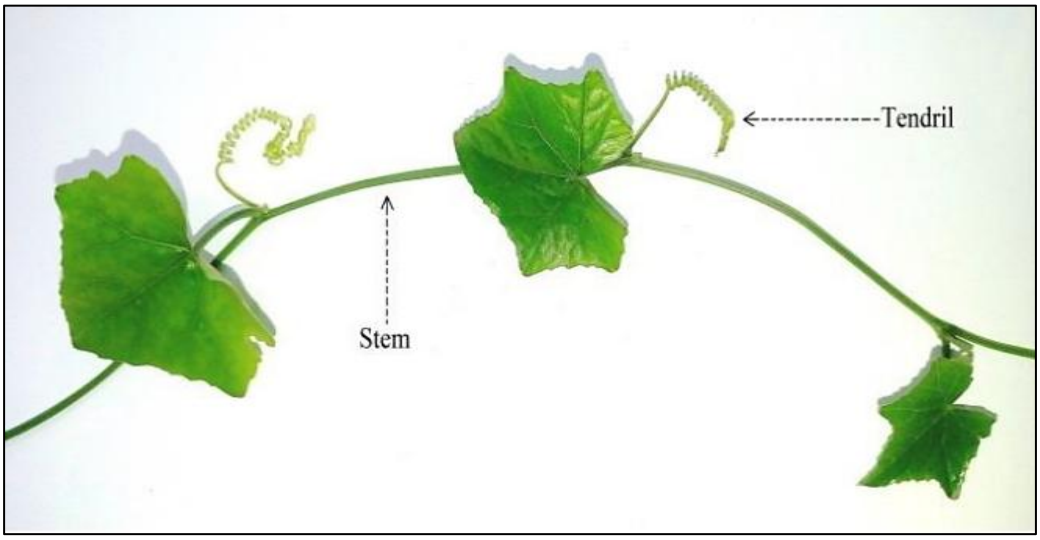

Fig. 1: Photograph of a segment of the *M. pendula* plant specimen used in the study showing the tendrils

Development of an instrument to study the mechanical property of tendril

The tendril of a plant is a spring-like special organ that helps a plant to anchor to a support. In the present work in order to study the mechanical (strain) property of a plant tendril a specialized instrument was developed in the laboratory based on Hook's law experiment on elasticity. The instrument was divided into two segments – lower base (B) and upper base B2. At the lower base a weighing balance set up was mounted and at the upper base a specially designed manipulator system was mounted perpendicularly (Fig. 2).

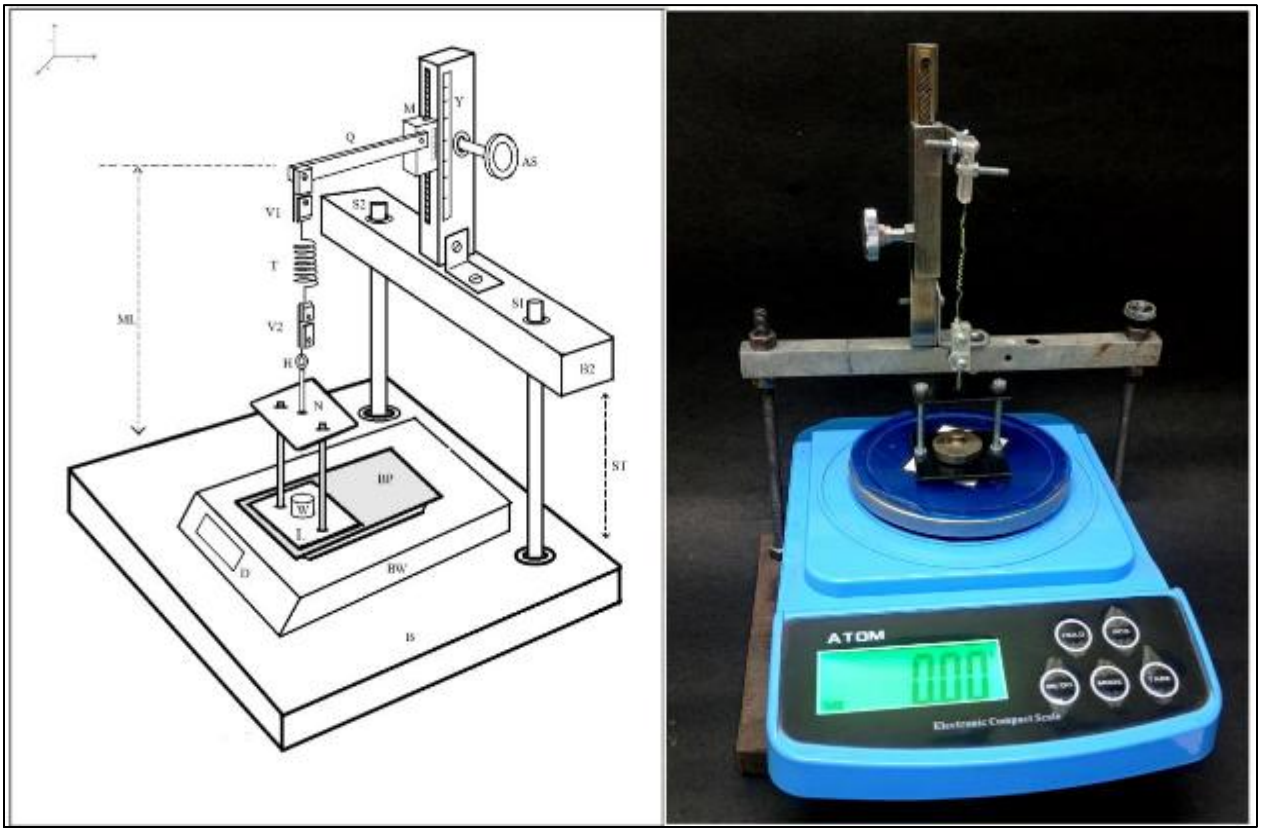

Fig. 2: The Tendril Strain Quantification Instrument
a) Schematic diagram b) The instrument for studying the tendril mechanical property
B - lower base, B2 – upper base, ST – variable vertical distance between B and B2 by two adjusting screws S1and S2, M – manipulator system, Y – Vernier scale, AS – manipulator vertical adjustment knob, Q – extension rod, V1-V2 – tendril vise 1 and 2, T – tendril sample, H – hook, N – top portion of load applied segment, L – bottom portion of load applied segment, W – applied weight, BW – weighing balance, BP – weighing balance plate, D – digital display, ML – variable vertical distance between manipulator system and lower base of the instrument

The distance between these two bases could be varied vertically as per the experimental requirement by means of two adjusting screws. For clamping the tendril two specially designed delicate vises (V1 and V2) were developed. The V1 vise was attached with the manipulator system through an extended connecting rod (Q). The weighing balance was aligned in such a way so that the weight measuring plate of this weighing balance maintained the same axis as that of the vise V1. The instrument also consisted of a specially designed load applied segment. This load applied segment was carefully placed on top of the weighing balance plate in a manner so that it maintained the same axis of the V1 vise. This load applied segment had two subparts – top and bottom. At the bottom part the desired weight was carefully placed and the top part was coupled to the other vise V2. Thus, the vises V1 and V2 were ultimately aligned vertically along the same imaginary axis.

In between the vises V1 and V2 the two ends of the delicate tendril were carefully clamped for experimentation (Fig. 3). Now, when the manipulator system was displaced vertically upward or downward by the adjusting knob the distance between the two vises underwent variation. As a result of this variation, the weight placed on the load applied segment functionally exerted its effect on the clamped tendril. The effect of this acting weight was then recorded at the digital display of the weighing balance.

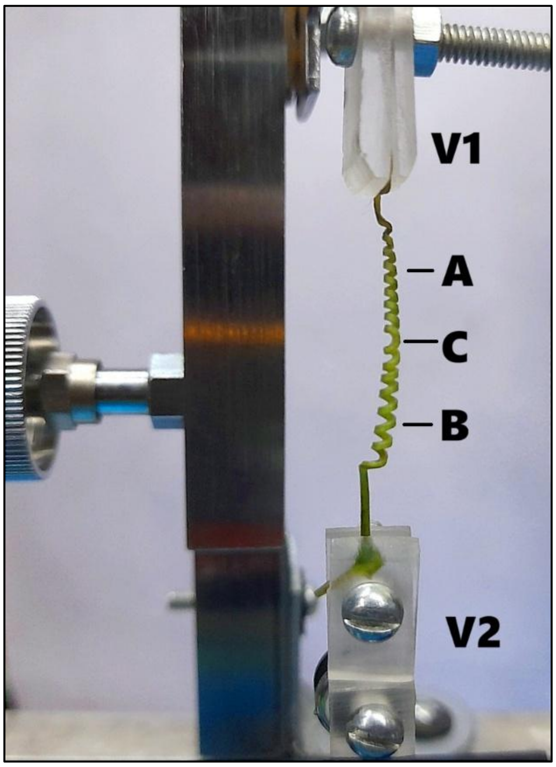

Fig. 3: Pictorial representation of the part of the experimental set up highlighting the vises holding the bidirectionally coiled tendril along the fine manipulator arrangement

V1 and V2 – Tendril clamping vises, A – Left spiral (counter clockwise) helix of tendril, B – Right spiral (clockwise) helix of tendril, C – Perversion stretch

Experimental Procedure

For the present study two types of tendrils, a) tendril with both clockwise and counterclockwise coiling and b) tendril with unidirectional coiling was taken from the climbing plant *M. pendula* (Fig. 4). The mechanical property of the tendrils was quantitatively studied in terms of mechanical strain (relative lengthwise deformation, compared to a reference position configuration following an applied load) using the developed Tendril Strain Quantification Instrument. For the experimentation the tendrils were coupled delicately between the two vises V1 and V2 (Fig. 2) and in the load applied segment the particular intensity of load was placed and the weighing balance measuring scale was set to 0. Following this, using the manipulator system the applied load was linearly uplifted each time through 1 mm displacement in a direction vertically opposite to that of acting applied load. As a result of this displacement the set 0 value of the weighing scale changed to negative value in the increasing order. Each time this change in the displayed load (g) with respect to 1 mm displacement was noted and later computed for graphical representation. The applied load (force) and the recorded displacement was later converted to dyn and cm respectively, as per the CGS metric system. The applied force (in dyn) was plotted in the Y-axis and the displacement (cm) was plotted in the X-axis for obtaining the respective force-displacement curves of the different tendril types [11, 12].

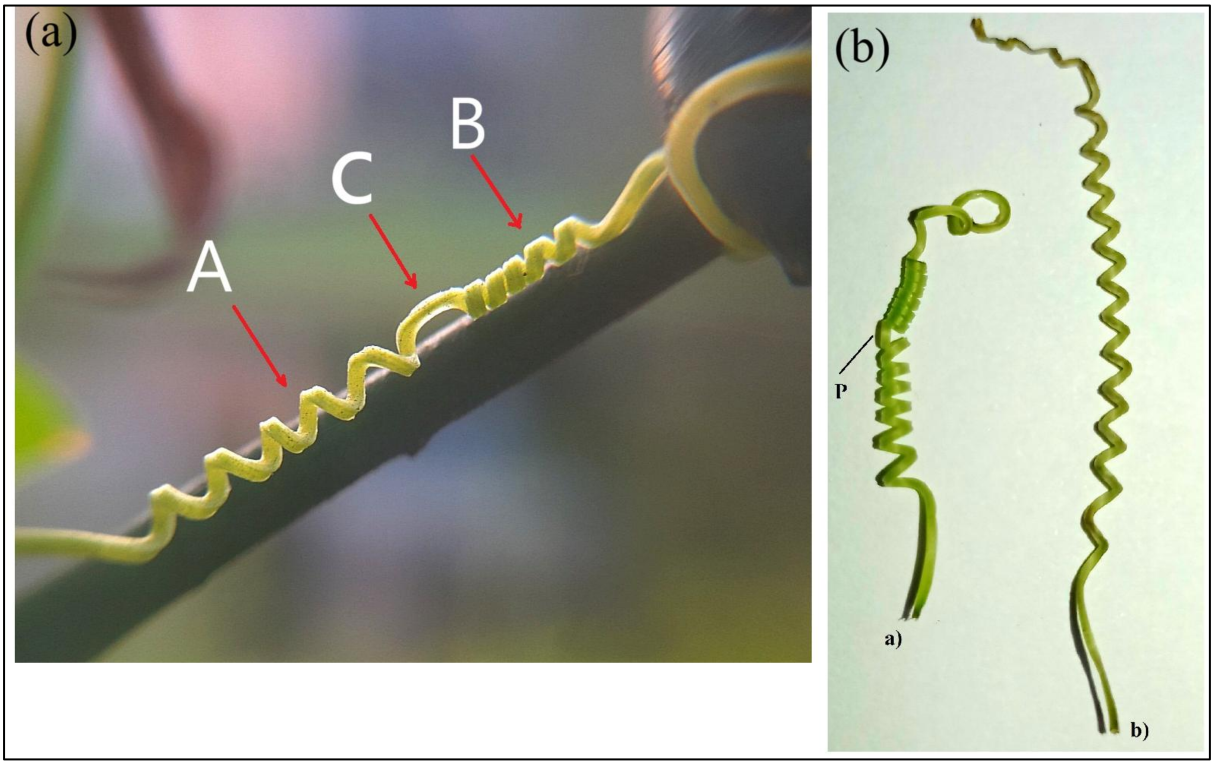

Fig. 4: The two different types of tendrils used in the study

(a) Labelled image of a double helical tendril and (b) Image of both the tendril types

a) Bidirectionally coiled tendril; b) Unidirectionally coiled tendril; A – Right spiral (clockwise) helix of bidirectionally coiled tendril, B – Left spiral (counter clockwise) helix of bidirectionally coiled tendril, C and P – linear stretch of perversion

IV. RESULTS AND ANALYSIS

The results of the present study have been presented in the form of displacement corresponding to the applied force. Initially the force-displacement curve was plotted up to the linearity limit for both the tendril types (Fig. 5). Following this, a comparative analysis was performed in terms of the mechanical property between the clockwise and clock-counterclockwise tendril. From the present study it was found that in case of tendril with uni-directional coiling the response curve exhibited linearity at 0.8 cm displacement corresponding to the force of -6903.88 dyn (load). However, in case of tendril with both clock and counterclockwise coiling the response curve exhibited a relatively greater linearity at 1.2 cm displacement corresponding to the force of -3383.29 dyn (load). Thus, the results indicated that the unidirectionally coiled tendril reached the linearity limit at a much earlier displacement of 0.6 cm, however, the bidirectionally coiled tendril attained the linearity limit at a much later displacement value of 1.2 cm. The whole experiment using both the types of tendrils was repeated thrice and each time the data pattern was similar.

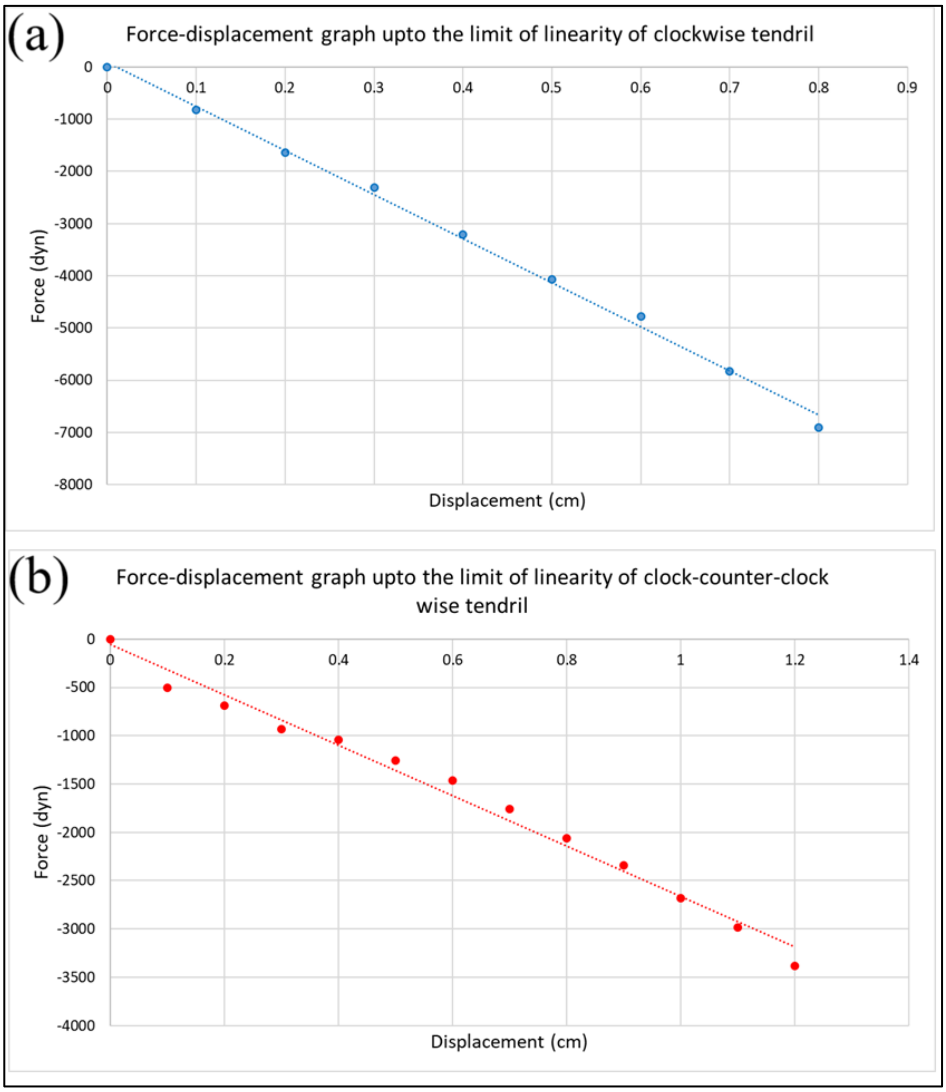

Fig. 5: The Force-Displacement Graphs of the (a) clockwise tendril and (b) clock-counter-clockwise tendril up to the linearity limit

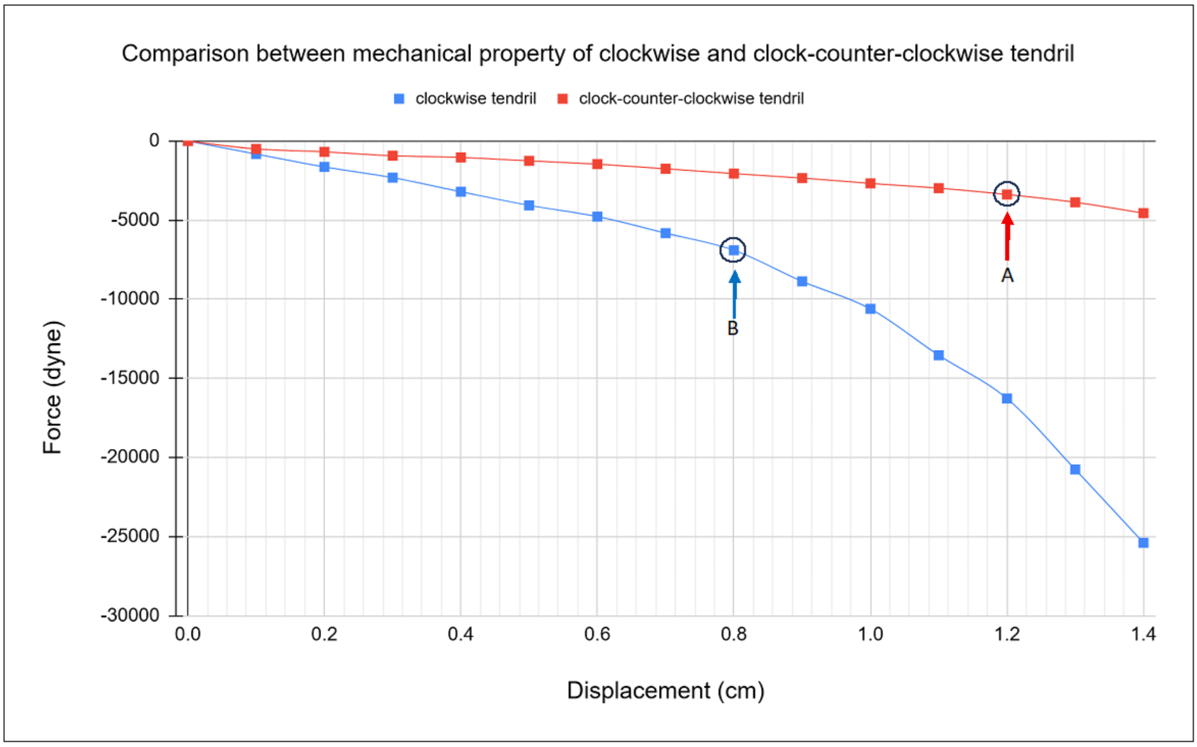

Fig. 6: Comparative Analysis between the mechanical property of the two types of tendrils obtained using the Tendril Strain Quantification Instrument

A – Linearity Limit of Clock-Counter-Clockwise Tendril; B – Linearity Limit of Clockwise Tendril

The relevant physical dimensions were measured. In the table the physical dimensions of the two types of tendrils used for the study, have been presented (Table 1).

Table 1: Tabular Representation of the physical dimension of the two different tendrils used in experimentation

Physical dimensions	*One-directional coiled tendril*	*Clock-counterclockwise coiled tendril*
Total no. of coil turns	12	6 (clockwise) + 6 (counterclockwise) = 12
Coil diameter (mm)	2	1 (clockwise), 1.7 (counterclockwise)
Tendril length (mm)	25	14
Tendril fiber thickness (mm)	0.3	0.4
Total applied weight (g)	33.1	33.1

Apart from quantitative analysis of the mechanical strength between the two tendril types, the present study also involved, development of 2 artificial bioinspired springs that were designed and developed based on the geometry of natural plant tendrils. One spring was unidirectionally coiled and the other was bidirectionally coiled with a perversion stretch. From the study it was also found that in case of the unidirectionally coiled spring, upon application of load there was a prominent angular rotation of the spring, as evident from the indicator on the protractor scale (Fig. 7A). However, no such angular rotation was visible in case of the bidirectionally coiled spring after application of load of same intensity (Fig. 7B).

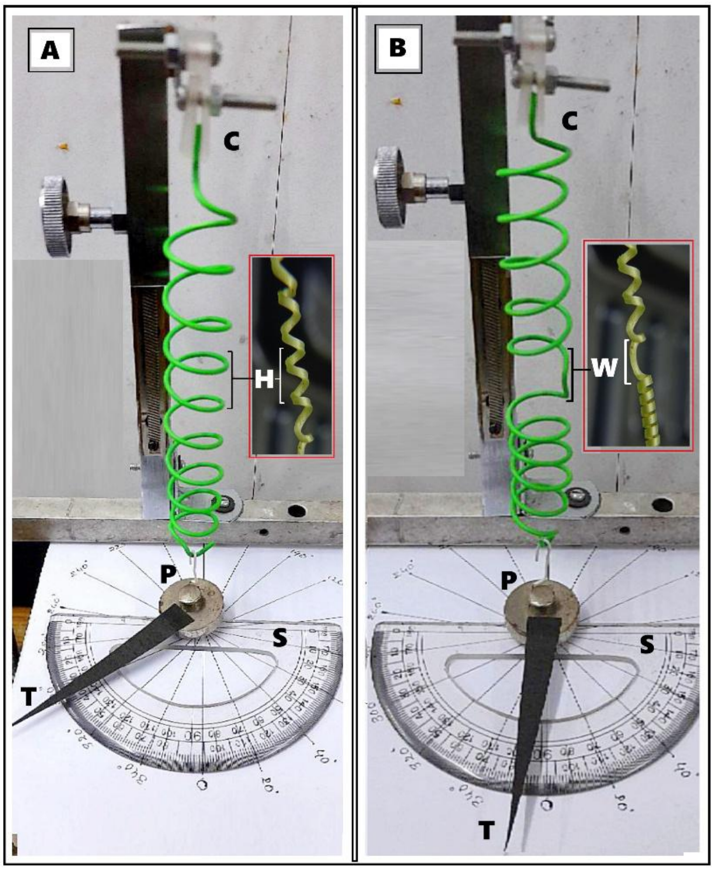

Fig. 7: The experimental set up of the bio-mimicked artificial springs developed on the basis of plant tendrils showing the variation in degrees of axial rotation following application of load

V. DISCUSSIONS

In the present work, in order to study the mechanical (strain) property of the tendril of *M. pendula* plant the specialized instrument developed in the laboratory was based on Hook’s law experiment on elasticity. For studying the mechanical property of the tendril two types of tendrils were selected from the model plant – one with uni-directional helix and the other with two-opposite directional helices (clock-counterclockwise) (Fig. 74). In case of the bi-directional helical tendrils, the tendril coiling may start with left-handed helices first which would then be interrupted by a short linear stretch and from the other end of this stretch the right-handed helices would resume or vice versa. This phenomenon of regularity breaking is known as tendril perversion [13]. Thus, in the present study the two types of tendrils used may be divided into helical tendril and tendril with perversion. To compare the mechanical property between the two types of tendrils, both the tendrils used were selected in such a way so that the total no. of coil turns were constant, i.e., 12. Moreover, in the tendril with perversion the total no. coil turns were equally opposing in no., i.e., 6 clockwise turns and 6 counterclockwise turns.

In the present study from the change in lengthwise displacement (cm) vs variable intensities of applied mechanical load (dyn) curve it was found that in case of the helical tendril the linearity limit was obtained at 0.8 cm displacement corresponding to -6903.88 dyn load. However, in case of tendril with perversion the linearity limit was obtained at 1.2 cm displacement corresponding to -3383.29 dyn load. Thus, the curve indicates that in case of tendril with perversion the attained linearity limit (at 1.2 cm displacement) was higher than that of the helical tendril (which attained linearity relatively earlier at 0.8 cm displacement). Therefore, it is suggestive of the fact that tendrils with perversion may act as better springs in comparison to that of helical tendrils. Similar kind of research works performed on helical and perversion tendrils have also reported that perversion tendrils have better spring-like functions than helical tendrils [14]. Studies have also reported that the tension force of the tendril helical structure increases linearly first and then nonlinearly with the displacement, i.e., the helical structure quickly stiffens [15]. Thus, the forces in the cases of perversion tendrils with two / three helices would be larger than that of one helix, suggesting that the perversion could effectively improve the elasticity of the tendril helical structure [16]. The study findings also indicated that following application of load (same intensity), the helical tendril (unidirectionally coiled) exhibited visibly higher rotation, compared to that of double-helical tendril (bidirectionally coiled).

In the study, the biomimicked spring model was developed following the geometry of plant tendril. Two types of springs (wounded wires) were developed – one with clockwise helix only and the other with both clock and anti-clockwise helix. The two spring types were clamped with the customized tendril mounting vise at one end and the other end was kept free, where identical weights were placed, so that there remains provision for unhindered axial rotation of the free end (in presence of the applied weight). The whole set up was then made to rest on a platform. Following this, the weight was uplifted till a certain displacement through the spring (fixed for both the spring types) from the base platform using the manipulator set up. From the observations it was found that in case of the single helical spring, which was supported at one end with a weight hanging from the other end, it experiences a downward pull, it undergoes rotation because the spring's coils act as a spiral or helix. As the spring extends, the tension forces it to untwist or twist further, resulting in an axial rotation. When a force (such as the hanging weight) pulls the spring downwards, it creates a twisting moment (torque) along the wire itself, which translates into rotational motion at the unconstrained end [17]. However, in case of the double helical spring, when it was displaced in presence of the weight of identical intensity, the amount of axial rotation was visibly negligible. The probable reason for the reduced axial rotation was due to opposing torsional movements of the oppositely coiled (clock and anti-clockwise) helices [18]. Previous studies have reported that in a double helical spring configuration the downward axial load induces the clockwise helix to twist in one direction and the anticlockwise helix to twist in the opposite direction [19]. The torsional forces and resulting angular rotations are equal in magnitude but opposite in direction. This causes the acting rotational forces to cancel each other out.

The findings therefore collectively indicate that the double helical plant tendrils as found in nature, in most combinations, may exhibit better spring-like properties in comparison to single coiled tendril. Thus, such nature inspired technological inclusions may prove to be plausible in development of innovative technologies in the near future.

VI. CONCLUSIONS

The study successfully demonstrated the biomechanical advantages of tendril perversion in *Melothria pendula* through a custom-built testing apparatus based on Hooke’s Law. Quantitative force-displacement analysis revealed that bidirectionally coiled tendrils (with perversion) exhibited higher linearity limit (1.2 cm displacement at -3383.29 dyn) compared to unidirectionally coiled helical tendrils (0.8 cm displacement at -6903.88 dyn). This indicates that tendril perversion yields superior elastic performance and may act as more efficient biological spring.

Furthermore, bio-mimicked wire models proved that single-helical structures suffer from high axial rotation and torque under tension. In contrast, the opposing geometry of bidirectional helices generates equal and opposite torsional forces that effectively cancel each other out, achieving negligible axial rotation. By neutralizing destructive twisting moments, tendrils with perversion structurally optimize structural stability and mechanical strength. These insights into self-compensating torsional mechanics offer an excellent blueprint for the biomimetic development of highly stable, nature-inspired spring systems and advanced engineering components. Thus, the evolution of bidirectionally coiled tendrils offer higher mechanical advantages to the plants in terms of enhanced linearity limit, as evident from the study findings.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgement

The authors pay gratitude to Late Prof. Ratan Lal Brahmachary and Late Prof. Dipankar Ray. The authors acknowledge Prof. Utpal Ghosh and Prof. Jishu Naskar of the Department of Biochemistry and Biophysics, University of Kalyani. The authors also thank Dr. Rajen Haldar, Dr. Suparna Mandal Biswas, Dr. Kuntal Ghosh and Ms. Tiyasa Mishra.

References

1. Bose, J. C. (1906). *Plant response as a means of physiological investigation*. Longmans, Green and Company.
2. Dilly, É., Derr, J., & Zanchi, D. (2026). Internal Stress Controls Tendril Writhing Dynamics in Climbing Plants.
3. Hansen, A., Gladala-Kostarz, A., Hindhaugh, R., Doonan, J. H., & Bosch, M. (2025). Mechanical stimulation in plants: molecular insights, morphological adaptations, and agricultural applications in monocots. *BMC biology*, *23*(1), 58.
4. Dilly, É., Derr, J., & Zanchi, D. (2026). Internal Stress Controls Tendril Writhing Dynamics in Climbing Plants.
5. Teng, P., Cai, Y., Liu, X., Tuo, Y., Wu, S., Wang, Q., ... & Wang, S. (2025). Inspiration of plant-related adhesion for plant wearable sensor interface design. *Nanoscale*, *17*(21), 13057-13075.
6. Hao, Y., Qiu, M., Dai, K., Zheng, G., Liu, C., & Shen, C. (2025). Tendril-inspired programmable soft actuator based on bilayer thermoplastic film. *Chemical Engineering Journal*, *503*, 158524.
7. Yang, X., Bai, L., Huang, X., Zhang, G., Lin, X., Li, L., ... & Yuan, D. (2025). Helical Morphing of Liquid Crystal Elastomer Fibers for Tendril-like Actuation. *ACS Applied Materials & Interfaces*, *17*(36), 51193-51200.
8. Wijerathne, B., Liao, T., Jiang, X., Zhou, J., & Sun, Z. (2025). Plant-inspired surfaces and interfaces for sustainable technologies. *Materials Futures*, *4*(1), 012301.
9. Zhen, L., Yu, L., Chen, X., Cui, M., Bai, X., Liu, J., & Yang, B. (2025). Tunable bioinspired spiral-structured piezoelectric vibration sensor for voice biometrics. *Chemical Engineering Journal*, *517*, 164513.
10. Dawran, A. J., & Zhang, D. (2026). Bio-Inspired Hierarchical Adhesive Interface for Continuous Physiological Monitoring: Design, Fabrication and Clinical Validation. *Big. D*, *3*(1), 99-115.
11. Guo, Q., Dong, J. J., Liu, Y., Xu, X. H., Qin, Q. H., & Wang, J. S. (2019). Macroscopic and microscopic mechanical behaviors of climbing tendrils. *Acta Mechanica Sinica*, *35*(3), 702-710.

12. Hu, G., Jiang, J., Zhang, Z., Zhang, Y., Brand, U., & Kim, M. S. (2017). Investigation of a small force standard with the mass based method. *Acta Imeko*, *6*(2), 13-20.
13. Aziz R, Barman A, Bhattacharjee U, Kumar R, Kalita E, Ray SK. Tendril perversion in cucurbits. Everyman's Science, 289-94, 2016.
14. Gouin, H. (2025). Climbing plants--Wrapping elastic plant stems around a cylindrical stake. *arXiv preprint arXiv:2507.15414*.
15. Prombanchong T, Suriyawong A, Srisongkram P, Suwanpayak N. Anatomical and physical properties of tendril perversion of Coccinia grandis (L.) Voigt. *In.* IOP Conference Series: Materials Science and Engineering, IOP Publishing, 965, 012011, 2020.
16. Dilly, É., Derr, J., & Zanchi, D. (2026). Internal Stress Controls Tendril Writhing Dynamics in Climbing Plants.
17. Li, W., Lou, C., Liu, S., Ma, Q., Liao, G., Leung, K. C. F., ... & Xuan, S. (2025). Climbing plant-inspired multi-responsive biomimetic actuator with transitioning complex surfaces. *Advanced Functional Materials*, *35*(6), 2414733.
18. Liang, H., Zhou, C., Wu, Y., Wang, S., Liu, R., Wang, S., ... & Hao, G. (2025). Plant-inspired robotics: a comprehensive review based on on-/off-plant behaviours and future perspectives. *Mechanical Sciences*, *16*(2), 771-797.
19. Dilly, É., Neukirch, S., Derr, J., Brett, W., & Zanchi, D. (2025). Mechanical instabilities and snapping phenomena in helical rods with perversion. *Journal of the Mechanics and Physics of Solids*, 106402.