1. INTRODUCTION

Lotus, an aquatic perennial widely cultivated in India, Asia, Australia, China, and Japan, typically grows in swamps and shallow waters. The natural cellulose from lotus fibers is associated with continuous rings inside the peduncles lying under the epidermis of vascular tissue. The lotus leaf’s excellent and stable superhydrophobicity is due to a combination of optimal traits such as surface topography, toughness, and the epicuticular wax’s unique qualities. The Lotus effect has encouraged researchers to create superhydrophobic surfaces and to design materials with enhanced hydrophobicity.

Nanomaterials have played a prominent role in altering size and structure at the nanoscale level to achieve and mimic the property mentioned above. 2D materials are currently recognized as nanomaterials having a sheetlike shape and a substantial lateral dimension ranging from hundreds of nanometers to tens of micrometers or even greater but only a single or few atomic layer thickness. Transition-metal dichalcogenides, noble metal dichalcogenides, MXenes, hexagonal boron nitride, organics/polymers, and transition-metal halides are some examples of innovative 2D materials beyond graphene. Of these, transition-metal dichalcogenides (TMDCs) have a one-of-a-kind amalgamation in-direct bandgap, approving electronic and mechanical properties, spin–orbit solid coupling, and thickness on the atomic scale, making them appealing for elementary research as well as applications that include personalized medicine, flexible electronics, high-end electronics, energy harvesting, DNA sequencing, optoelectronics, and spintronics. TMDCs are made up of three atomic planes and often two atomic species: a metal and two chalcogens. TMDCs have a generic formula of $\text{MX}_2$ where $M$ denotes transition metal and $(M = V, Zr, Ti, Ta, Hf, Nb, W, Co, Tc, Ir, Re, Pd, Rh, Ni, Mo, and Pt$) and $X$ denotes chalcogen ($X= Te, S, \text{and } Se$). The layered metal chalcogenides encompass a wide range of electrical characteristics from real metals (NbS$_2$) to superconductors (TaS$_2$) to semiconductors (MoS$_2$) with a wide variety of bandgaps and offsets.

Among many TMDC’s, MoS$_2$ has grown in popularity as a research topic, with applications in various fields, including transistors, photodetectors, and solar cells. The ultimate
The objective of developing such materials is to create better composites with a synergistic impact or provide a structural reinforcement.\textsuperscript{11−13} Since then, several nanoscience and nanotechnology journals have focused on the area of 2D materials. MoS\textsubscript{2} possesses a hexagonal arrangement consisting of S−Mo−S covalent bonds, and between the neighboring layers of MoS\textsubscript{2} there is a van der Waals interaction that allows them to be mechanically separated to form two-dimensional nanosheets.\textsuperscript{14} The two-dimensional MoS\textsubscript{2} nanosheets have various physical and chemical properties and possess several applications. Recent research on MoS\textsubscript{2} has revealed this as a solitary contender in hydrogen storage, supercapacitors, sensors, electrocatalysis, and other applications such as electronic sensors, biomedical engineering, and other applications. The remarkable unique properties include a great amount of surface area and absorption in the near-infrared band, thus providing a new outcome in biological applications.\textsuperscript{15} Biomedical uses for 2D MoS\textsubscript{2} sheets have been recently explored as well. In their seminal work, Zhu et al. explained that MoS\textsubscript{2} monolayers could be used to identify DNA molecules based on their fluorescence quenching capabilities. MoS\textsubscript{2} sheets have been employed as an NIR photothermal agent to kill Hela cells using their near-infrared (NIR) absorption. It has been reported that PEG-functionalized MoS\textsubscript{2} sheets can be used to transport drugs.\textsuperscript{16}

The utilization and manipulation of the thread’s wicking qualities for building programmable microfluidic channels have been the focus of thread-based research. So far, researchers have been looking for appealing substrate materials for decades to keep microfluidics advancing and overcome the disadvantages and difficulties such as tedious and expensive fabrication methods. Because of their unique structural and mechanical qualities, cellulose substrates such as thread and paper are considered as viable solutions for various applications.\textsuperscript{17−21} Thread has demonstrated many potential applications in diagnostic systems, smart bandages, and tissue engineering.\textsuperscript{22} Thread-based microfluidics is still in its infancy, and additional developments in manufacturing, analytical methodologies, and function are required before they can be commercialized as a low-cost, low-volume, and simple-to-use point-of-care (POC) diagnostic devices.\textsuperscript{23−26} Because of its features like flexibility, portability, biodegradability, lightweight, high tensile strength, and availability, several attempts have been made to employ thread for low-cost diagnostics or detection, among other low-cost materials such as paper and plastic.\textsuperscript{27−30} Liquid wicking in the thread is caused by the twisted strands of cellulose fiber and the space between them.

In this work, for the first time, we have incorporated 2D TMDC MoS\textsubscript{2} nanomaterials on natural threads obtained from lotus fibers (Figure \ref{fig:Figure1}). Since MoS\textsubscript{2} nanocomposites are widely used for diode fabrication,\textsuperscript{31} dye removal processes,\textsuperscript{32} high-performance microwave absorbers,\textsuperscript{33} fuel oil separation,\textsuperscript{34} tunable microwave absorbers,\textsuperscript{35} and electromagnetic wave absorption capability,\textsuperscript{36} the idea of drop-casting 2D-nanomaterials on a cellulose fiber can offer a different perspective for wearable sensors. Integration of thread devices (natural and synthetic) with 2D nanomaterials for enhanced hydrophobicity and antimicrobial activity remains unexplored. There has been an increasing interest in discovering and producing novel antimicrobial agents from numerous sources in recent years to tackle microbial resistance. As a result, antimicrobial activity screening and evaluation methodologies have received more attention.\textsuperscript{37} Antimicrobial susceptibility testing can be utilized in drug development, epidemiology, and treatment outcome prediction. Natural products derived from prokaryotes, eukaryotes, and other organisms are a significant source of therapeutic molecules and essential in identifying antimicrobial drugs.\textsuperscript{38} Therefore, pure threads and threads@MoS\textsubscript{2} are assessed for their potential antimicrobial properties against \textit{Escherichia coli} and \textit{Candida albicans} under light and dark conditions. MoS\textsubscript{2} was synthesized using the coprecipitation technique and further characterized through XRD and FESEM.\textsuperscript{39}

2. EXPERIMENTAL METHODS

2.1. Materials Used. Chemicals used in this research work were used as purchased. Sodium molybdate dihydrate (Na\textsubscript{2}MoO\textsubscript{4}·2H\textsubscript{2}O, Sisco laboratories, 99%), thiourea (CH\textsubscript{2}CSNH\textsubscript{2}, Loba Chemie, 99%), and hydrochloric acid (HCl, Merck Life, 37%) were purchased. Standard strains of \textit{E. coli} (ATCC 25922) and \textit{C. albicans} (ATCC 24433) were obtained for testing antimicrobial properties from the Department of Microbiology, Kasturba Medical College, Manipal. Nutrient Agar and Sabouraud Dextrose Agar with chloramphenicol were procured from Himedia, India.

2.2. Extraction of Lotus Fiber. Lotus stems were collected at Kolarampathy Lake in Coimbatore, Tamil Nadu, with a latitude of \textdegree{}10.973400 and longitude of \textdegree{}76.909850. Ideally, flowers should be fully bloomed so that the deep pink blooms contain the finest lotus fibers. The collected fibers are then trimmed, snapped, and twisted. The twisted fibers reveal 20–30 fine white filaments pulled and wrapped into a single thread.

2.3. Preparation of the MoS\textsubscript{2} Nanoparticle. The MoS\textsubscript{2} nanoparticle-coated lotus fiber was synthesized through the coprecipitation method. Na\textsubscript{2}MoO\textsubscript{4}·2H\textsubscript{2}O (6 mmol) was dissolved in deionized water (80 mL) and stirred well (30 min) for homogeneous mixing. Then 12 mmol of CH\textsubscript{2}CSNH\textsubscript{2} was added to the above solution. The well-washed (with Millipore water and ethanol) lotus fiber thread was dipped inside the solution, and then the solution was heated to 65 °C. HCl was included dropwise to the mother solution at 65 °C.

![Figure 1. Schematic illustration of coating 2D-MoS\textsubscript{2} nanosheets on lotus threads.](https://doi.org/10.1021/acsomega.2c02337)
The colorless solution turned dark blue. The heat treatment continued, and a color change from dark blue to brown and then eventually to chocolate brown within 10 min of adding HCl was observed. The temperature of the solution was maintained at 80 °C for 1 h. The particles were left overnight for the settlement. The collected particles, which were then centrifuged for 10 min at 3500 rpm, were washed and dried at 55 °C and collected.

2.4. Characterization. The structure of the coated fiber was examined by a Philips PAN analytical Xpert pro powder X-ray diffractometer with Cu Kα (1.54 Å). Morphology and elemental analysis of pure and MoS₂-coated lotus fiber were recorded using an S-3400 N Hitachi field emission scanning electron microscope (FESEM).

The hydrophobicity of the uncoated and MoS₂ nanoparticle-coated lotus fiber threads (3 cm length) was assessed by measuring the water penetration rate in the thread pieces. A 100 μL portion of phenol red dye solution in water was added to one end of the threads placed over an overhead projector (OHP) sheet, and images of the threads were captured at defined time intervals using a Canon Eos 3000D DSLR camera and further analyzed using FIJI software.

The water absorbency of the uncoated and coated fibers (1 cm length) was determined by measuring the dry weight of the threads using a weighing balance then dipping the thread pieces in 1 mL of water for 5 min to measure the wet weight of the threads. The percentage of water absorbency was measured using the following formula:

$$\text{% water absorbency} = \frac{\text{wet weight} - \text{dry weight}}{\text{wet weight}} \times 100$$  \hspace{1cm} (1)

The contact angle measurements for the uncoated and coated fibers were analyzed using the KYOWA Interface Measurement and Analysis System through a sessile drop method.

2.5. Antimicrobial Properties. Culture suspensions of E. coli and C. albicans spiked in water were prepared, adjusted to 0.5 McFarland standard concentration, and inoculated on Muller Hinton Agar (MHA) and Sabouraud Dextrose Agar (SDA) with chloramphenicol, respectively. The uncoated and MoS₂ nanoparticle-coated lotus fiber threads (UV sterilized, 10 mm length) were plated on the agar media in the inoculated plates and incubated under two different conditions to check the antimicrobial property of the threads. The first plate was incubated at 37 °C under ambient light, whereas the other plate was incubated at 37 °C under dark conditions (covered with aluminum foil to block ambient light) for 24 h.

3. RESULTS AND DISCUSSION

3.1. Structural Studies. XRD analysis of Pure and MoS₂ coated lotus thread was carried out for analyzing its structure. Patterns of pure lotus fibers were well matched with cellulose crystalline standards. Observed XRD reflections of lotus fibers are well matched with the cotton Iβ cellulose. The cotton Iβ cellulose reference pattern was taken from CIF file no. 4114994 using the Mercury 3.8 program. Comparative patterns of experimental (fiber) and calculated (cotton Iβ cellulose) are depicted in Figure 2. The comparison clearly shows that the obtained major reflection for lotus fiber planes such as (1−10), (110), (102), and (200) were well matched with the calculated one with a broader pattern. The recorded pattern of fiber@MoS₂ is presented in Figure 3 and was compared with the calculated standard with CIF file no. 9007660 of MoS₂, which exhibits a hexagonal structure. The obtained composite pattern clearly shows that the wide pattern at (002) reveals the thin layers of MoS₂ sheets. Mugashini et al. confirm the thin layer of MoS₂ nanosheets. The high crystalline peak of MoS₂ at the (100) plane supports the island growth nature of MoS₂.

Figure 2. Comparative XRD pattern of lotus fiber and calculated cotton Iβ cellulose patterns.

Figure 3. Comparative XRD pattern of MoS₂@fiber and calculated MoS₂.
planes (100), (101), (102), and (103) confirm the island formation.

3.2. FESEM Analysis. The morphology and surface of the pure and MoS\textsubscript{2}-coated lotus thread samples were investigated for FESEM. Figure 5 represents the SEM images of pure lotus fiber at different magnifications. Figure 6 depicts the SEM images and EDX of MoS\textsubscript{2}-coated fibers. Excellent moisture absorption and permeability due to the twisted ribbon-like structure were observed. The twisted helical structures of the fibers are observed. With increasing magnification, the H-shaped cuts required for water transportation are visible. Fibers appear slender, and veins are seen in the transverse view of the fiber. The cracks that occurred during fiber extraction are noticed. Damaged areas with cracks result in a fine layer of MoS\textsubscript{2} nanosheets. The nanosheets arise vertically on the fiber’s surface, which also appears as H-cuts. The appearance of frequent H-cuts makes fiber water repellent. The diameter of the pure fiber is 2.92 \( \mu \)m, whereas the diameter of fiber@MoS\textsubscript{2} is 2.89 \( \mu \)m.

3.3. Antifungal Activity. The Agar disk-diffusion method is one of the standard techniques used to determine the antimicrobial activity of materials and compounds against bacteria and fungi \textit{in vitro}. Conventionally, the filter paper discs with the imbibed test compound are placed on the agar media plates inoculated with the organism cultures, and the zone of inhibition of growth around the discs is studied to determine the antimicrobial property of the test compound.\textsuperscript{37,45–47} Similarly, in our study, we have checked for the presence of a zone of inhibition of growth formed around the uncoated and MoS\textsubscript{2} nanosheet coated lotus fiber threads placed on the agar media plates inoculated with \textit{C. albicans} culture and were further incubated at 37 \( ^\circ \)C. Under ambient light conditions, the MoS\textsubscript{2}-coated thread exhibited more antifungal activity than the uncoated or plain thread (Figure 7a). Similarly, the MoS\textsubscript{2}-coated thread exhibited more antifungal activity under dark conditions than the uncoated or plain thread (Figure 7b).

Interestingly, the zone of inhibition (ZOI) in the dark was more prominent than in the light experiments. We hypothesize that this may be due to the photosensitive nature of MoS\textsubscript{2} nanosheets in the presence of ambient light and dark conditions. The study confirms that the growth of fungi \textit{C.}
Figure 6. Different magnification SEM images (a−e) and EDX (f) of MoS$_2$-coated lotus fiber.

Figure 7. Antifungal activity of pure and MoS$_2$-coated lotus fiber under light (a) and dark (b) conditions.

Figure 8. Antibacterial activity of pure and MoS$_2$-coated lotus fiber under light (a) and dark (b) conditions.
albicans around the uncoated or plain lotus threads is attributed to no antifungal activity.

3.4. Antibacterial Activity. Figure 8 represents the antibacterial activity of uncoated and MoS$_2$-coated lotus threads under ambient light and dark conditions. Antibacterial activity of the MoS$_2$-coated lotus fiber thread was observed mainly under the dark conditions, depicted by the zone of inhibition of growth of E. coli formed around the coated thread. However, significant growth of the organism was observed around the uncoated or plain thread under both ambient light and dark conditions exhibiting no antibacterial activity. Thus, the antimicrobial studies conducted confirm the more antibacterial and antifungal activity of the coated nanoparticle lotus fiber threads under dark conditions than in ambient light. MoS$_2$ nanosheets can generate ROS and induce physical damage for bacterial inactivation. Basu et al. have shown the antifungal and antipollutant activity of MoS$_2$ nanosheets under dark conditions. Similarly, Alimohammadi et al. have reported that peptidoglycan mesh in the bacterial cell wall has been indicated as a primary target for interaction with the sheets leading to morphological changes and cell wall damage. A comparative table depicting the antimicrobial activity of MoS$_2$ by various researchers and has been summarized in the Supporting Information (Table S1).

3.5. Water Absorbance and Penetration Assay. On plain lotus fiber, the water absorbance is relatively high. Liu et al. confirmed the rate of faster absorption of water in the lotus fiber. On the other hand, lotus fiber coated with nanostructured MoS$_2$ has low absorbance, making it water resistant, which can be potentially integrated with fabrics. Figure 9 shows the water absorbency graph on pure and MoS$_2$-coated lotus fiber. Observation inferred that pure fiber makes a contact angle of 116°, and MoS$_2$-coated lotus fiber has a contact angle of 128°, indicating that MoS$_2$ coating improves the hydrophobicity of fiber. The contact angle value increases toward superhydrophobicity.

3.6. Contact Angle Measurements. Figure 11 shows the contact angle measurements of pure (a) and MoS$_2$-coated lotus fiber (b). Figure 10 gives the graphical representation for lateral water penetration on plain and MoS$_2$-coated fibers. Water penetration on plain lotus fiber increases gradually over a distance of 3 cm for the observed 60 min, whereas the fiber@MoS$_2$ shows no penetration, i.e., 0 cm for 60 min. Thus, the water penetration assay confirmed that no penetration occurs in fiber@MoS$_2$.

4. CONCLUSION

The coprecipitation method was used to assess the hydrophobicity and antimicrobial activity of MoS$_2$ nanosheets coated on lotus fiber. The XRD patterns confirmed the crystalline nature of pure fiber and fiber@MoS$_2$. FESEM reveals the morphology of fiber@MoS$_2$. The growth of MoS$_2$ nanoparticles over the fiber decreases the wicking ability, confirming the hydrophobic nature of the material. Further, antibacterial and antifungal activities of the MoS$_2$-coated fiber were verified with E. coli and C. albicans, respectively. The contact angle of fiber@MoS$_2$ is 128°, indicating its improved hydrophobicity to pure lotus fiber. The results further pave the way for developing self-healing sutures and bandages using natural lotus threads and 2-D nanosheets for point-of-care sensors and detection systems.

ASSOCIATED CONTENT

 Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.2c02337.
Antimicrobial activity of MoS₂ nanosheets (Table S1) (PDF)

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All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by S.S. Govarthini, D. Thangaraju, Anusha Prabhu and Naresh Kumar Mani. The first draft of the manuscript was written by S.S. Govarthini and D. Thangaraju, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. S.S. Govarthini: Writing - original draft. D. Thangaraju: Methodology, Conceptualization, Visualization, Methodology, Supervision, Writing - review and editing. Anusha Prabhu: Methodology, Writing - review and editing. Naresh Kumar Mani: Conceptualization, Visualization, Methodology, Supervision, Writing - review and editing.

Funding
D.T. sincerely thanks the Science and Engineering Research Board (ECR/2017/002974), Department of Science and Technology, Government of India, for the financial support. N.K.M. and A.P. acknowledge the financial support from Vision Group on Science and Technology, Government of Karnataka under SMYSR and RGS/F Scheme [Sanction Letter no.: KSTEPS/VGST/SMYSR-2016-17/GRD-595/2017-18, KSTEPS/VGSTRGS/F/GRD No.711/201711–18]. We extend our special thanks to the Department of Biotechnology, Manipal institute of Technology.

Notes
The authors declare no competing financial interest.

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