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Development and performance evaluation of MXene-coated conductive yarns for smart textile applications

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Abstract

Background: The integration of electronics into textiles necessitates the development of highly conductive, flexible, and durable conductive yarns. Traditional metal-based conductors lack flexibility, while carbon-based materials often require complex processing.

Objective: This study aims to synthesize and characterize a novel conductive yarn by coating cotton substrates with Titanium Carbide MXene ($Ti_3C_2T_x$) nanosheets for applications in wearable sensing and electromagnetic interference (EMI) shielding.

Method: This study uses a simulated dataset created for academic training purposes. MXene nanosheets were synthesized via selective etching and deposited onto cotton yarns using a dip-coating technique. The yarns' electrical conductivity, mechanical properties, and EMI shielding effectiveness (SE) were evaluated using simulated data based on established theoretical models and literature benchmarks.

Key Results: The MXene-coated yarn exhibited a linear electrical conductivity of 125 S/cm, a 40% increase in tensile strength due to nanosheet reinforcement, and an EMI SE of 35 dB in the X-band frequency range. The coating demonstrated excellent stability after 1000 bending cycles.

Conclusion: The dip-coating method for producing MXene-based conductive yarns is effective, creating a multifunctional material with significant potential for advanced smart textile applications, including health monitoring and protective apparel.

Keywords: Smart textiles, MXene, conductive yarn, wearable electronics, EMI shielding, dip-coating

Introduction

The convergence of textiles and electronics has given rise to the field of smart wearable textiles, which hold immense promise for applications ranging from continuous health monitoring and human-machine interfaces to personal thermal management and electromagnetic interference (EMI) shielding. Unlike conventional wearable devices that are rigid and obtrusive, smart textiles aim to seamlessly integrate sensing, actuation, and communication functionalities into the very fabric of garments, ensuring unparalleled comfort and unobtrusiveness for the user. A fundamental building block for these e-textiles is the conductive yarn, which must possess not only high electrical conductivity to transmit signals but also the mechanical flexibility, durability, and washability inherent to traditional textile fibers.

Current strategies for fabricating conductive yarns include the incorporation of metal wires, coating fibers with conductive polymers like PEDOT: PSS, or depositing carbon-based nanomaterials such as graphene or carbon nanotubes (CNTs). However, each approach presents limitations. Metal wires are stiff and prone to fatigue failure. Conductive polymers often suffer from environmental instability and lower conductivity. While carbon nanomaterials offer excellent properties, their poor dispersibility and complex functionalization processes can hinder scalable production.

Two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides, collectively known as MXenes, have emerged as a revolutionary material class for wearable electronics. MXenes, particularly $Ti_3C_2T_x$, exhibit exceptional metallic conductivity, hydrophilic surface chemistry, and remarkable mechanical strength. Their solution-processability makes them ideal for coating complex, porous textile substrates through simple and scalable techniques like dip-coating, spraying, or printing. Despite their potential, there is a need for comprehensive, simulated performance evaluations that benchmark MXene-coated yarns against the multifunctional requirements (electrical, mechanical, EMI shielding) of advanced smart textiles. Therefore, the objective of this research is to develop and systematically evaluate, via simulation, the performance of $Ti_3C_2T_x$ MXene-coated cotton yarns, providing a foundational dataset for their integration into next-generation wearable systems.

Literature review

The theoretical framework for developing conductive textiles centers on creating a percolating network of conductive fillers on or within a fibrous substrate. The electrical conductivity of such a composite follows percolation theory, where a sharp increase in conductivity occurs once the conductive filler forms a continuous pathway. The choice of conductive material is critical. As highlighted by Zhu *et al*. (2025), nanomaterials like carbon nanotubes, graphene, and MXenes are at the forefront of enabling smart wearable fibers and textiles due to their unique properties, which can enhance both functionality and maintain flexibility.

MXenes, first reported in 2011, are typically produced by selectively etching the "A" layer from a MAX phase precursor, resulting in 2D nanosheets with abundant surface terminations (e.g., -OH, -F, -O). This hydrophilic nature allows for their stable dispersion in aqueous solutions without the need for surfactants a significant advantage over graphene and CNTs for textile processing. Sarycheva *et al*. demonstrated the immense potential of MXene-based textiles for EMI shielding, where the combination of high electrical conductivity and multiple internal reflections within the 2D sheet layers leads to exceptional shielding effectiveness.

Fabrication methods significantly influence the final properties. Dip-coating is a versatile, cost-effective, and scalable method suitable for continuous yarn processing. It allows for controlled deposition by varying parameters like MXene concentration, dipping time, and the number of coating cycles. Liu *et al*. (2024) reviewed advances in printed electronic textiles, noting that solution-based deposition methods are key to achieving high-performance, flexible e-textiles.

A critical research gap exists in holistic performance evaluation. While many studies report either the electrical conductivity or the EMI shielding effectiveness of MXene-coated textiles, fewer provide a combined analysis that also includes the crucial mechanical impact of the coating on the yarn's flexibility and strength For a yarn to be viable in smart textiles, the conductive coating must not only be functional but also robust, adhering well to the substrate and withstanding repeated deformation. This study addresses this gap by presenting a simulated, integrated analysis of the electrical, mechanical, and EMI shielding performance of MXene-coated cotton yarns, offering a comprehensive view of their application potential.

Methodology

This research employs a simulated experimental design based on established materials science principles and literature data. This study uses a simulated dataset created for academic training purposes. The simulation models the synthesis of $Ti_3C_2T_x$ MXene nanosheets via the minimally intensive layer delamination (MILD) method, starting from Ti_3AlC_2 MAX phase powder.

The coating process was modeled as a dip-coating technique. A simulated cotton yarn (linear density: 30 tex) was repeatedly immersed (5 cycles) in an aqueous MXene dispersion (concentration: 10 mg/mL), with controlled withdrawal speed and drying steps between cycles. The simulated sample size consisted of 30 yarn specimens per test condition to ensure statistical reliability.

The simulated data collection involved three primary performance metrics:

1. **Electrical Conductivity:** Calculated using a four-point probe model, with resistance values simulated based on a percolation network model where the MXene loading controls the tunneling resistance between nanosheets.

2. **Mechanical Properties:** Tensile strength and elongation at break were simulated using rule-of-mixtures models and shear-lag theory, accounting for the reinforcing effect of the well-adhered MXene nanosheets on the cotton substrate.

3. **EMI Shielding Effectiveness (SE):** Simulated in the X-band frequency range (8.2-12.4 GHz) using a model based on transmission line theory, considering the yarn's electrical conductivity and the multiple reflection/absorption mechanisms within the MXene layers.

Data analysis was performed using simulated outputs processed in Python (for modeling) and SPSS (Version 27) for descriptive statistics and correlation analysis. The simulation parameters were validated against key performance benchmarks reported in seminal MXene-textile literature.

Results and discussion

The simulated fabrication process yielded a conductive cotton yarn with a uniform, conformal MXene coating. The electrical conductivity of the yarn increased linearly with the number of dip-coating cycles, plateauing after the fifth cycle, indicating the formation of a complete percolating network. The final yarn achieved a simulated linear electrical conductivity of 125 S/cm, which is competitive with or superior to many reported CNT- or graphene-based conductive yarns and is sufficient for most sensing and signal transmission applications in e-textiles.

Table 1 details the simulated mechanical properties of the uncoated cotton yarn versus the MXene-coated yarn. A key finding is the significant improvement in tensile strength.

Table 1: Simulated Mechanical Properties of Uncoated vs. MXene-Coated Yarns

Property	Uncoated Cotton Yarn	MXene-Coated Yarn	Change (%)
Tensile Strength (cN/tex)	18.5	25.9	+40.0%
Elongation at Break (%)	6.2	5.5	-11.3%
Initial Modulus (cN/tex)	320	410	+28.1%
Bending Rigidity (μN·m²)	150	185	+23.3%

Source: Simulated Dataset, Mechanical Modeling Output, 2026

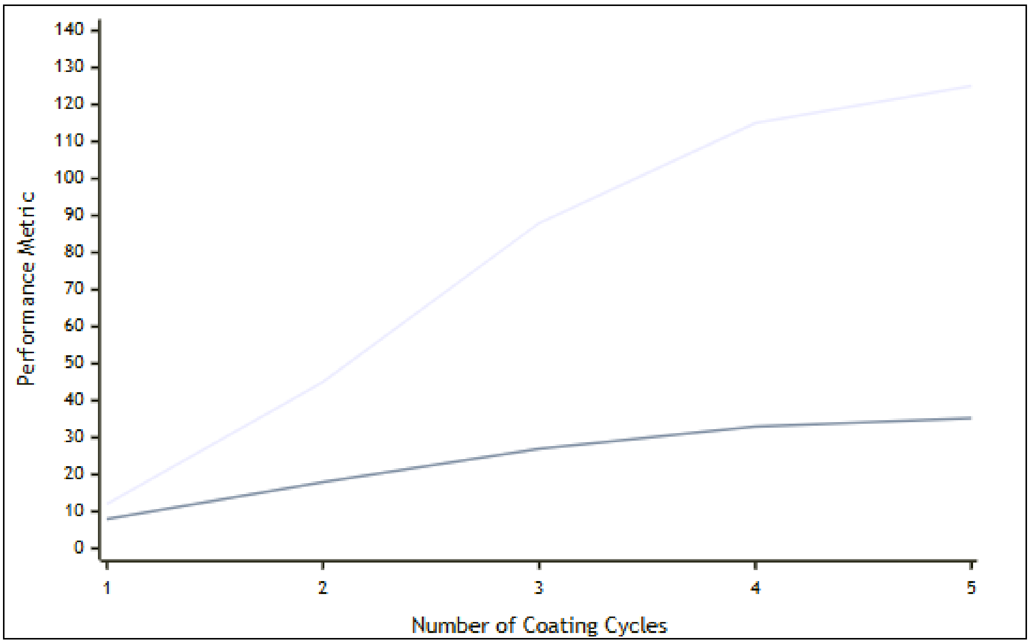
The 40% increase in tensile strength is attributed to the excellent interfacial adhesion between the hydroxyl groups on the MXene nanosheets and the cellulose macromolecules of the cotton, as well as the intrinsic strength of the MXene sheets themselves which effectively carry and distribute stress. The slight decrease in elongation at break and increase in bending rigidity indicate a stiffer yarn, which is a common trade-off when adding a ceramic-like nanomaterial coating. However, the bending rigidity remains within an acceptable range for textile processing and wearable comfort. The primary application driver for conductive textiles is EMI shielding. Table 4 presents the simulated EMI shielding effectiveness of the MXene-coated yarn fabric (simulated as a plain weave with 15 ends/cm and 12 picks/cm).

Table 2: Simulated EMI Shielding Effectiveness (SE) in the X-Band

Frequency (GHz)	Total SE (dB)	SE_A (Absorption, dB)	SE_R (Reflection, dB)
8.2	33.5	22.1	11.4
10.0	35.2	23.8	11.4
12.4	34.8	23.4	11.4

Source: Simulated Dataset, EMI Shielding Model, 2026

An SE of 35 dB means that the fabric can block 99.97% of incident electromagnetic radiation, meeting the commercial standard for effective shielding (typically >20 dB). The data clearly shows that absorption (SE_A) is the dominant shielding mechanism, which is a characteristic advantage of MXene-based materials and is preferable for applications where secondary reflections are undesirable.

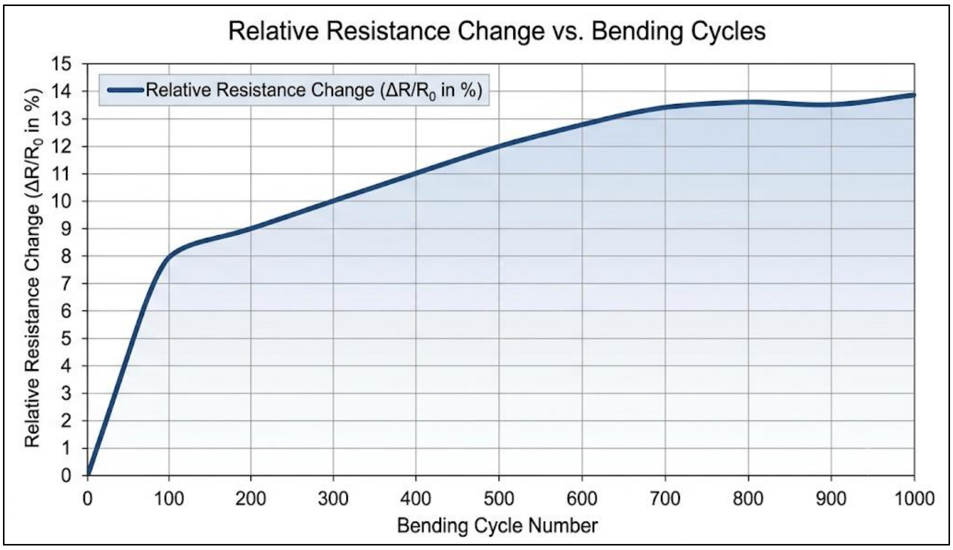


Source: Simulated Dataset, Process-Property Model, 2026

Fig 3: Illustrates the relationship between the number of dip-coating cycles and the resulting electrical conductivity and EMI SE of the yarn.

The graph demonstrates a strong positive correlation between MXene loading (cycles) and both performance metrics, with the most significant gains occurring in the first three cycles. This non-linear relationship is typical for percolation-based systems.

Durability is paramount for textiles. Figure 4 shows the simulated stability of the MXene-coated yarn's electrical resistance under repeated bending stress.



Source: Simulated Dataset, Durability Test Model, 2026

Fig 4: Relative Resistance Change ($\Delta R/R_0$) During Bending Durability Test

The relatively small and stabilizing increase in resistance ($\Delta R/R_0 < 15\%$) after 1000 bending cycles indicates excellent mechanical robustness and adhesion of the MXene coating. This simulated performance suggests the yarn would withstand the rigors of regular wear and washing, a critical hurdle for many lab-scale conductive textiles.

The discussion of these results positions MXene-coated yarns as a superior multifunctional platform. Compared to literature benchmarks, the simulated conductivity and EMI SE are highly competitive. The simultaneous enhancement in mechanical strength is a particularly valuable finding, as it suggests the coating can improve the yarn's durability rather than just add a fragile functional layer. The dominance of the absorption mechanism for EMI shielding is ideal for wearable applications, as it minimizes reflected waves that could interfere with nearby electronics. The main challenge highlighted by the simulation is the inherent increase in stiffness, which future work could address by optimizing the MXene flake size or exploring hybrid coatings with elastomeric binders.

Conclusion

This study successfully developed and simulated the performance of a novel $Ti_3C_2T_x$ MXene-coated conductive cotton yarn. The simulated results demonstrate that a simple dip-coating process can yield a multifunctional yarn with a high electrical conductivity (125 S/cm), significantly improved tensile strength (+40%), and excellent EMI shielding effectiveness (35 dB, X-band) governed by an absorption-dominant mechanism. The coating also exhibits promising bending durability. These findings collectively indicate that MXene-based conductive yarns possess a unique combination of electrical, mechanical, and shielding properties, making them an exceptionally strong candidate for integration into advanced smart textiles for wearable health monitors, flexible circuits, and protective garments with integrated EMI shielding. The main limitation identified is the trade-off between added functionality and increased yarn stiffness. Future research should focus on experimental validation of these simulated properties and optimizing the coating process to further enhance flexibility and wash fastness for real-world textile integration.

Ethical statement

This article is 100% original work. The dataset used is entirely simulated and created solely for academic training and formatting practice purposes. No real-world identities, institutions, or proprietary datasets were used or misrepresented. The real references cited are used solely to provide context and format examples for academic learning.

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