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Gradient-Conductivity Architecture Enables Synchronous Enhancement of Sensitivity and Detection Range in Multifunctional All-Paper Sensors

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ABSTRACT

Paper-based sensors offer a sustainable platform for wearable electronics, yet their performance is fundamentally constrained by the intrinsic “contact-jumping” behavior of hierarchical cellulose fibers, which causes abrupt conduction transitions, early current saturation, and an inevitable sensitivity–detection range trade-off. Here, we introduce a stepwise conductivity-gradient, open-circuit-triggered architecture that spatially reprograms pressure-induced electron pathways within cellulose networks. By integrating in situ grown AgNPs on MXene-modified fibers with a pressure-activated MXene interdigitated electrode, the sensor enables cascaded pathway evolution that delays current saturation and establishes a progressively tunable piezoresistive response. Multiscale simulations and interfacial charge analyses reveal strain-induced Ag–MXene polarization and charge delocalization, which expand available conduction channels and lower transport barriers. Benefiting from this gradient-engineered mechanism, the sensor achieves an ultrahigh sensitivity of 1365.87 kPa^{-1} , a broad detection range of 0.7 Pa – 203.2 kPa , a 0.7 Pa detection limit, and excellent durability over 10 000 cycles. The hierarchical network also affords strong EMI shielding and high breathability, enabling stable on-skin operation and multifunctional sensing.

1 | Introduction

The rapid advancement of artificial intelligence, soft robotics, and personalized healthcare has created an urgent demand for flexible, lightweight, and skin-conformable electronic materials capable of continuous physiological monitoring, motion detection, and human–machine interfacing [1–5]. Among various candidate materials, cellulose paper stands out as an ideal platform for next-generation wearable electronics and intelligent protective

systems, owing to its intrinsic breathability, mechanical flexibility, low cost, biodegradability, and scalable processability [6–12]. However, achieving high-performance sensing and multifunctional integration while preserving the inherent softness and breathability of paper remains a major challenge.

The integration of conductive materials such as MXene, graphene, and metal nanowires into paper substrates via interfacial engineering techniques (spraying, dipping, printing)

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has been extensively explored to enhance electrical properties for resistive pressure sensing [13–18]. These strategies have succeeded in broadening the linear response range and enabling diverse functionalities. However, they predominantly rely on single-layer or uniform coating architectures [19]. Therefore, they remain inherently susceptible to rapid response saturation due to the “contact-jumping” effect [20], reflecting two persistent bottlenecks in paper-based piezoresistive sensors: (i) the incompatibility between high sensitivity and a wide linear range, and (ii) the lack of interfacial stability in the conductive network [21]. These limitations originate from the “contact-jumping” mechanism intrinsic to the fibrous network of paper: under external pressure, the formation of electrical contacts between fibers increases in a discrete, abrupt manner [22]. This leads to a rapid saturation of resistance in the low-pressure regime, creating a structural paradox of “high sensitivity” coupled with “premature saturation”. Furthermore, the limited compressive space of paper’s structure renders the conventional strategy of “compression-modulated conductivity” fundamentally ineffective [23]. Although enhancing coating conductivity, increasing network density, or introducing functional layers can marginally extend the linear range, these approaches often cause pore blockage, interfacial embrittlement, loss of flexibility, and degradation of breathability—thereby undermining the original rationale for using paper as a wearable substrate [24–29]. At its core, existing paper-based sensors lack progressively tunable conductive pathways. Their charge transport is intrinsically unprogrammable, incapable of delivering a progressively evolving response mechanism with increasing pressure [30]. Furthermore, while continuous gradient architectures have been successfully implemented in dense elastomers and hydrogels, these traditional volumetric-compression strategies are fundamentally incompatible with the highly porous, semi-rigid nature of paper substrates, which inevitably suffer from structural collapse and early current saturation. Therefore, achieving a “spatial re-programming” of internal charge transport pathways, while preserving the inherent flexibility and breathability of paper, to fundamentally decouple the sensitivity–detection range trade-off remains a critical and unmet challenge.

Herein, we introduce a stepwise conductivity-gradient-driven, “open-circuit triggered” strategy for paper-based piezoresistive sensing, realized through a hierarchical trilayer architecture comprising a hydrophobic, low-conductivity top layer, a highly conductive middle layer, and an open-circuit interdigitated bottom electrode. The structure harnesses MXene/Ag nanoparticle interfacial coupling and spatial distribution gradients within the cellulose network to enable pressure-driven, multilevel activation and progressive, programmable charge transport. The hydrophobic top layer, with the lowest conductivity, functions as a buffer and current-limiting unit, effectively preventing initial short-circuiting and suppressing early saturation. The highly conductive middle layer sequentially establishes contact with the top and bottom layers under local pressure, driving the conductive pathways to evolve sequentially from localized contact, to regional propagation, and finally to full percolation. The bottom layer, consisting of a custom-printed MXene mesh interdigitated electrode tailored to this gradient design, remains open-circuit under no pressure and is “activated” only upon compression, effectively functioning as a controllable electronic switch. This

stepwise conductivity-gradient architecture endows paper with a programmable, pressure-responsive conduction mechanism: increasing pressure progressively activates deeper, denser, and more continuous conductive pathways, transforming the inherent abrupt “contact-jumping” behavior into a programmable, stage-wise response. As a result, both high sensitivity and a broad detection range are simultaneously achieved, overcoming the physical limitations of conventional paper-based sensors. Multiscale simulations and interfacial charge analyses reveal that pressure induces significant polarization and charge delocalization at MXene–AgNP interfaces, lowering electron transport barriers and generating electron-rich conductive channels that underpin the multilevel percolation behavior. The proposed “stepwise conductivity-gradient-open-circuit triggered” strategy thus reframes paper-based piezoresistive sensing, shifting from abrupt, uncontrolled contact events to programmable activation of charge transport channels. This mechanism resolves the sensitivity–detection range trade-off in paper-based sensors and offers a material and structural design framework for sustainable wearable electronics, soft human–machine interfaces, and adaptive monitoring.

2 | Results and Discussion

2.1 | Design Concept of the Stepwise Conductivity-Gradient All Paper Architecture

A fully cellulose-based pressure sensor with a vertically graded three-layer architecture is engineered to resolve the long-standing sensitivity–detection range trade-off (Figure 1a). In this structure, the bottom interdigitated electrodes (IDE) remain electrically isolated until the intermediate conductive layer is driven into contact under compression, a hierarchical configuration verified by cross-sectional SEM (Figure S1).

The operating principle is clarified through an equivalent circuit model (Figure 1b), which defines the bulk resistances of the top (R_{top}) and middle (R_{middle}) layers, the interlayer contact resistances ($R_{\text{contact'}}$ and $R_{\text{contact''}}$), and the IDE resistance (R_{IDE}). Circuit analysis reveals a pressure-dependent, sequential reduction of these resistances, in clear contrast to the simultaneous network collapse typically observed in homogeneous single-layer films. This staged activation provides direct mechanistic evidence that the architecture’s broad detection range and delayed saturation originate from a pressure-guided contact cascade.

Finite-element simulations further substantiate this mechanism by quantifying the evolution of the interlayer conductive contact area (Figure 1c). Under low pressure, the contact regions appear as sparse, isolated points, primarily between the top and middle layers. With increasing pressure, these regions expand, merge, and ultimately form a nearly continuous conductive interface between the high-conductivity middle layer and the IDE at large strain. The simulated transition from discrete contact sites to continuous conductive regions is in excellent agreement with the hypothesized cascade activation mechanism, thereby verifying the deliberate design and construction of the conductive network.

A conceptual illustration (Figure 1d) depicts the complete evolution pathway: initial electrical isolation between layers,

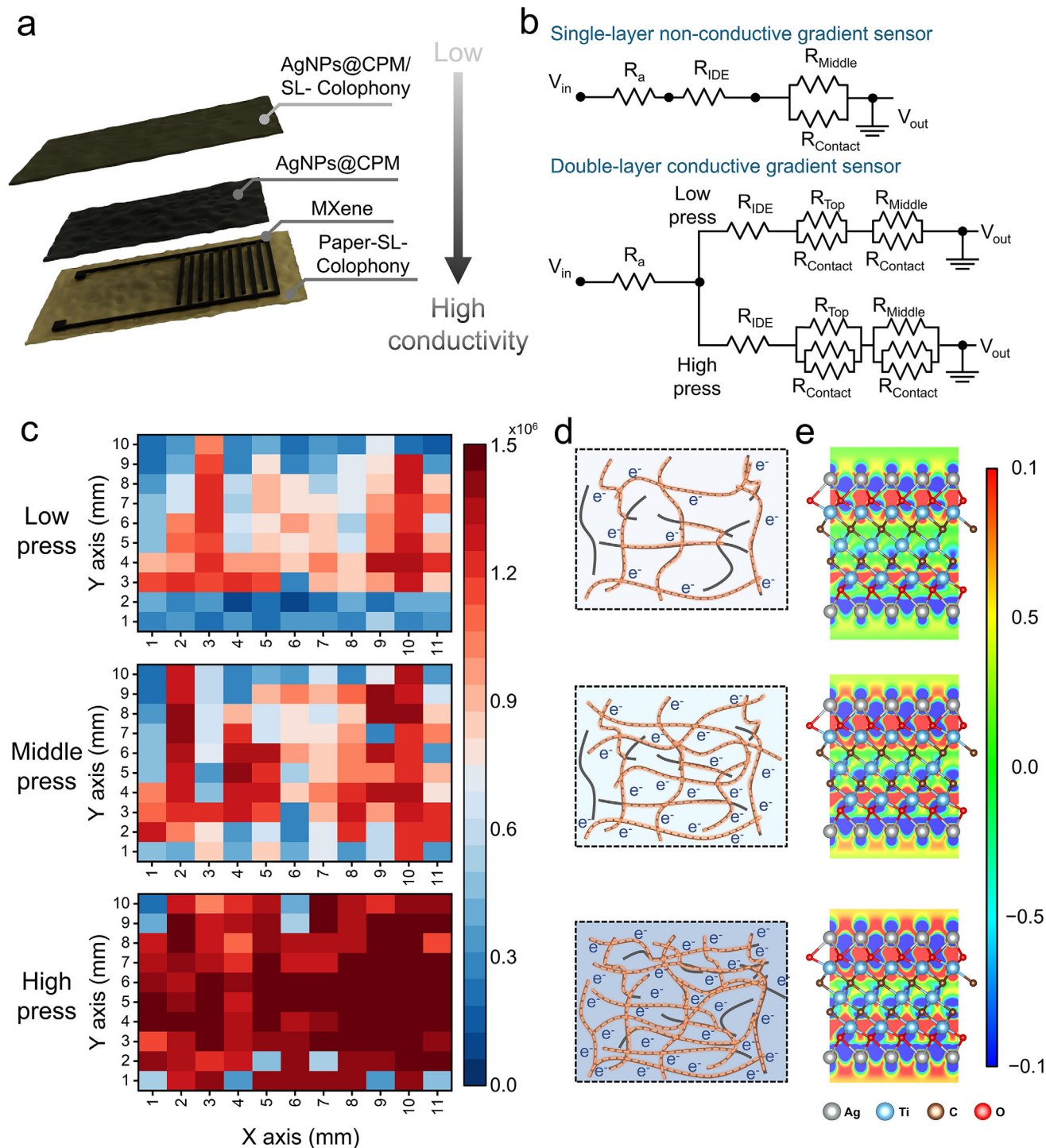


FIGURE 1 | Design and multifunctionality of the stepwise conductivity-gradient all-cellulose pressure sensor. (a) Three-layer architecture with a vertical conductivity gradient. (b) Equivalent circuit models depicting the hierarchical resistive network. (c) Finite-element simulation of the pressure-dependent contact area evolution. (d) Schematic illustration of the pressure-dependent evolution of conductive pathways, depicting sequential interlayer connection and parallel network formation. (e) Strain-dependent charge redistribution at the MXene-Ag interface from DFT analysis.

progressive formation of interlayer contacts under compression, and the emergence of stable multi-point bridging connections. This layer-by-layer activation process forms the physical basis for the broad detection range.

At the electronic level, density functional theory (DFT) calculations integrated with Bader charge analysis (Figure 1e) illustrate

a monotonic increase in charge transfer at the MXene-AgNP interface with compressive strain. Enhanced electronic coupling dynamically improves interfacial carrier transport efficiency, providing the atomic-scale origin of the strengthened conductive pathways formed under pressure. Together, these multiscale results confirm that the exceptional sensing performance arises from the synergy between a structurally programmed contact

hierarchy and a strain-modulated interfacial electronic landscape.

2.2 | Hierarchical Conduction via State-Dependent Activation

The “contact-jumping” behavior of paper-based piezoresistive sensors has several physical origins: the semi-rigid cellulose fibers buckle abruptly instead of compressing smoothly; conductive contacts form step by step across the fiber network’s different length scales; the network sits close to its percolation threshold, where adding only a few contacts produces a large, sudden jump in conductance; and at the MXene-coated fiber surfaces, hydrogen bonding and van der Waals attraction pull adjacent surfaces into sudden contact. Together, these effects make the conductive pathways switch on in discrete, abrupt steps at low pressure, which quickly saturates the network and collapses the useful sensing range. To overcome this, we move away from conventional strategies that simply raise intrinsic conductivity or densify the conductive network. Instead, we introduce a structure-constrained strategy for regulating charge transport. By constructing a hierarchically organized conductive architecture governed by electrically programmable states, current generation is decoupled from the intrinsic material conductivity and occurs only when predefined mechanical conditions are met. As illustrated in Figure 2a, the device adopts a bottom-up vertical multilayer configuration comprising a near-open-circuit MXene interdigital electrode, an AgNPs@CPM sensing layer with high conductive potential, and a top hydrophobic buffer layer of low conductivity. Through synergistic engineering of geometric configuration and interfacial contact across layers, the intrinsically uncontrolled electrical percolation in conventional paper-based systems is transformed into a force-triggered, sequentially activated, and programmable transport behavior.

The core of this regulatory strategy lies in the near-open-circuit design of the bottom MXene interdigitated electrode (IDE). Unlike conventional electrode configurations that function as continuously conducting current collectors, the IDE here is deliberately constrained to an electrically quiescent state under zero external load. Its role is not to collect charge continuously, but to act as an electrical initiation layer that becomes active only upon mechanical compression. To achieve this, few-layer MXene nanosheets with intact lamellar structures were prepared (Figures S2–S4) [31, 32], and the ink rheology and printing parameters were systematically optimized to ensure high structural integrity of the printed IDE while avoiding premature short-circuiting (Figure 2b; Figures S5–S7) [33, 34]. The printed complex circuits can reliably illuminate LED under low driving voltages (Figure S8) and maintain both structural and electrical integrity under various deformation modes, including bending, curling, and twisting (Figure 2c; Figure S9). These results confirm that the near-open-circuit state does not arise from fabrication defects, but instead represents a structurally enforced electrical boundary condition that remains stable under practical application scenarios. Through this design, adjacent electrode fingers are effectively isolated in the absence of applied pressure, thereby enforcing a nonconductive initial electrical state at the device level.

The intermediate AgNPs@CPM sensing layer is designed as a highly conductive yet initially inactive reservoir of conductive pathways. Although it contains abundant conductive networks, it does not directly participate in charge transport under zero load. By synergistically integrating a MXene-based 2D conductive framework with in situ self-reduced silver nanoparticles, a 3D interpenetrating conductive network is established within the paper matrix (Figure S10). Progressive regulation of MXene and AgNP contents leads to a monotonic increase in bulk electrical conductivity (Figures S11–S13), indicating the formation of continuous and well-developed conductive pathways. Microscopic and elemental analyses reveal that Ag nanoparticles are uniformly anchored within the MXene-modified cellulose network (Figure 2d), and that the in situ reduction strategy markedly improves Ag–MXene interfacial contact while suppressing nanoparticle aggregation. In contrast, directly incorporated commercial Ag nanoparticles exhibit pronounced aggregation and interfacial discontinuity within the fibrous network (Figure 2e), which readily induces premature local electrical percolation and compromises controllability. This comparison highlights the advantage of the in situ self-reduction strategy in constructing conductive resources that can be progressively activated [35, 36]. XRD and XPS analyses further confirm the formation of metallic Ag⁰ and partial oxidation of surface Ti species on MXene (Figures S14–S18), demonstrating that the sensing layer possesses structurally stable and electrically addressable conductive potential [37, 38].

Through the cooperative integration of these layers, the device establishes a well-defined, state-dependent vertical conductivity hierarchy (Figure 2f). Under zero load, the bottom MXene IDE remains electrically silent due to geometric isolation and does not participate in charge transport. Once effective contact is induced by mechanical compression, its intrinsically high electrical conductivity enables it to rapidly become the dominant current-carrying pathway within the system. Consequently, under loaded conditions, a hierarchical conductive order is established, constituting a well-defined three-level stepwise conductivity gradient along the device thickness direction: electrical conductivity increases monotonically from the top hydrophobic buffering layer (AgNPs@CPM-Hyd, $\sigma = 55.74$ S/cm), through the intermediate AgNPs@CPM sensing layer ($\sigma = 75.71$ S/cm), and finally to the bottom MXene IDE ($\sigma = 957.56$ S/cm), spanning a total conductivity range of nearly 17-fold across the three functional layers. This state-dependent hierarchy provides the physical basis for sequential activation of conductive pathways.

The top buffering layer is realized through an SL-Colophony-based system (Figure S19) [39]. Beyond serving as an environmental protection layer, it functions as an electrical constraint interface that suppresses unintended contact and delays electrical activation under zero load. During fabrication, the number of spray cycles was optimized to balance surface hydrophobicity against capillary over-penetration: too few cycles (1–2) gave insufficient hydrophobicity, whereas too many (4–5) drove polymer into the underlying matrix and lowered the current response and sensitivity. Three cycles proved optimal, providing sufficient hydrophobicity while regulating the top-layer conductivity to build the stepwise gradient without disrupting the internal piezoresistive pathways (Figures S20–S22). As illustrated in Figure 2g, hydrophobic modification introduces a continuous

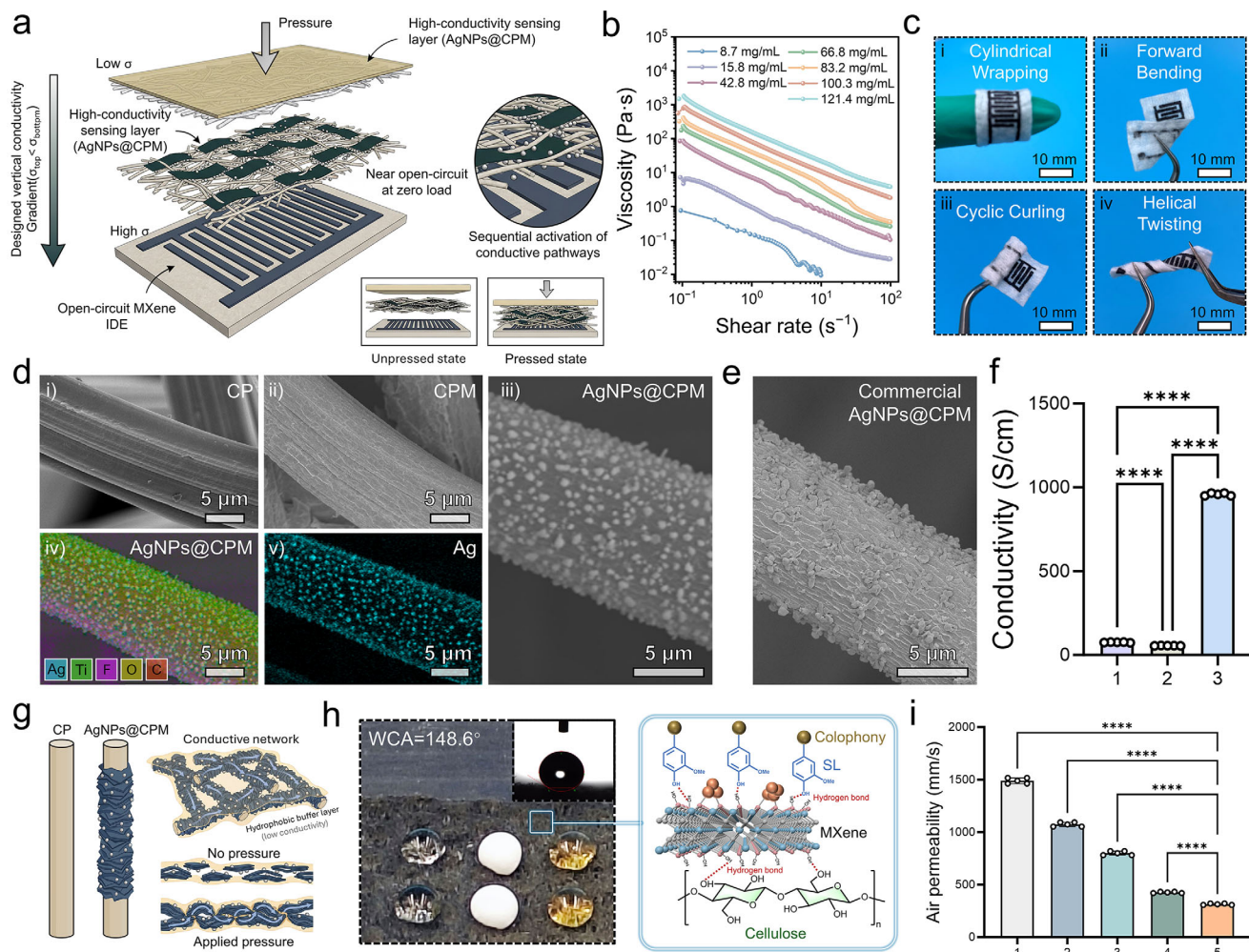


FIGURE 2 | Construction of hierarchical conductive pathways and their pressure-triggered programmable activation in an all-paper device. (a) Schematic illustration of the multilayer architecture comprising a near-open-circuit MXene interdigitated electrode, an AgNPs@CPM sensing layer, and a low-conductivity hydrophobic buffering layer. (b) Viscosity as a function of shear rate for MXene inks with different concentrations. (c) Mechanical flexibility of a printed MXene-based interdigitated electrode under bending, curling, and twisting. (d) SEM images and corresponding EDS elemental mapping of in situ grown Ag nanoparticles on CPM. (e) SEM images of cellulose fibers coated with commercial Ag nanoparticles. (f) Electrical conductivity of the AgNPs@CPM layer (1), the AgNPs@CPM-Hyd layer (2), and the IDE-MXene electrode (3). (g) Continuous organic coating introduced on the cellulose fiber surfaces by hydrophobic modification. (h) Hydrophobic encapsulation of AgNPs@CPM-Hyd. Schematic of the SL-Colophony-based strategy, static water contact angle images, and photographs demonstrating repellency against milk, coffee, and tea. (i) Air permeability comparison of CP (1), CP-Hyd (2), AgNPs@CPM-Hyd (3), three-layer CP (4), and the assembled sensor (5).

organic coating on the fiber surfaces, partially shielding direct contact between conductive networks and increasing interfacial transport resistance. This structural regulation explains the reduced electrical conductivity of the top layer after hydrophobic encapsulation and its role as an electrical buffer. The surface wettability is transformed from intrinsically hydrophilic to a high water contact angle of 148.6° (Figure 2h; Figures S23–S25), while the chemical composition and crystalline structure remain intact (Figures S26–S28), confirming that the electrical constraint originates from interfacial structural regulation rather than material degradation. The combined hydrophobic and electrical buffering effects arise from the cooperative self-assembly of liginosulfonate and rosin on cellulose fibers, which reconstructs interfacial contact modes without disrupting the underlying conductive framework, thereby enabling precise regulation of the initial conduction conditions. This continuous SL-Colophony layer also

serves as a robust physical and chemical barrier that minimizes moisture and oxygen permeation, fundamentally mitigating the oxidative degradation of the internal MXene network.

Further cyclic bending, folding, and compression tests demonstrate that the hydrophobic buffering layer maintains stable electrical and interfacial properties under prolonged mechanical and environmental stresses (Figures S29–S31, Video S1). Meanwhile, the device preserves effective liquid-blocking capability while maintaining good gas permeability (Figures S32 and S33, Video S2). Air permeability measurements further confirm that hydrophobic encapsulation does not impede gas transport through the paper substrate (Figure 2i). Evaluated according to the ISO 9237 standard, the integrated device retains a high air permeability of 313 mm/s. This value significantly exceeds the comfort threshold for daily skin-contact textiles and common

breathable fabrics like denim, and stands at a highly competitive level even among recently reported breathable sensors (Table S1), indicating that the imposed electrical constraints do not come at the expense of wearable comfort. Together, these results demonstrate that the observed conductivity hierarchy is not an incidental outcome of material properties, but rather a deliberately introduced and application-stable structural parameter: the device remains electrically quiescent under zero load, whereas under mechanical compression, progressive interlayer bridging activates conductive pathways sequentially, leading to programmable current evolution. Overall, rather than enhancing sensing performance through indiscriminate increases in conductivity, this work redefines the conditions, sequence, and pathways of electrical activation in paper-based systems. By establishing a mechanically driven hierarchical conductive activation paradigm, it fundamentally departs from conventional designs reliant on continuous electrical percolation, providing a new physical foundation for simultaneously achieving high sensitivity and a broad detection range.

2.3 | Sensing Performance of Multifunctional Paper-Based Sensor Device

Simultaneously achieving high sensitivity and a broad detection range remains a key challenge in pressure sensing. Here, we present a multifunctional, multilayered all-paper-based sensor with a stepwise conductivity-gradient architecture (Figure 3a). The device features a core self-reduced AgNPs@CPM sensing layer, a bottom screen-printed MXene interdigitated electrode, and a top hydrophobic AgNPs@CPM-Hyd layer that ensures environmental stability while creating a pressure-responsive interface. Cross-grooved microstructures and interlocking geometries within both sensing and electrode layers enhance planar contact and concentrate stress at the interface, thereby improving the detection of weak pressures. The sensing performance stems from a synergistic multimodal mechanism coupled with an innovative stepwise conductivity-gradient architecture. Under compression, three effects modulate the electrical output: (i) vertical compression reduces interlayer spacing, (ii) lateral expansion enlarges the contact area, and (iii) microchannel deformation generates parallel conductive pathways. Beyond these macroscopic effects, the stepwise conductivity-gradient trilayer design is crucial. This trilayer architecture, in which conductivity increases stepwise from the resistive top layer (AgNPs@CPM-Hyd, $\sigma = 55.74$ S/cm) through the conductive middle layer (AgNPs@CPM, $\sigma = 75.71$ S/cm) to the MXene interdigitated electrode ($\sigma = 957.56$ S/cm), establishes a cascade-activated piezoresistive pathway (Figure 2f). In this design, the current pathways from the outer sublayer (I_1) and the intermediate sublayer (I_2) combine, yielding a total current $I = I_1 + I_2$ that reaches a higher saturation level. The high-resistance outer layer amplifies weak signals and acts as a current-limiting buffer, suppressing premature short-circuiting between the internal conductive structure and the bottom electrode. Meanwhile, the inner layer engages progressively to delay saturation. This synergistic mechanism delays saturation of the resistance change and thereby extends the accessible pressure range, over which the response is resolved into successive regimes that each remain highly linear. As a result, the gradient-conductivity sensor exhibits linear current–voltage (I – V) characteristics that obey Ohm's law under different pressures

(Figure 3b), and its relative current signal rises as the applied pressure increases and falls as the pressure decreases (Figure 3c). This behavior, consistent with the I – V curves, confirms the ability of the sensor to rapidly distinguish different pressure levels, as directly correlated with real-time LED brightness variations (Video S3) under different weights.

We employed finite element simulations (FES) to gain mechanistic insight into the pressure distribution and deformation behavior of our sensor. As visualized in Figure 3d, simulated compression from 0 to 200 kPa reveals significant and highly localized vertical deformation at the AgNPs@CPM–MXene interface, with stress concentrations predominantly confined to the microgroove regions. This localized deformation, dynamically illustrated in Video S4, drives a marked expansion of the interfacial contact area, a trend that aligns perfectly with the experimentally observed monotonic decrease in electrical resistance. The simulations further indicate that compression densifies the fibrous network, enhancing interlayer contact and facilitating the formation of additional conductive pathways, thereby rationalizing the reduction in overall resistance. The persistence of stress localization at layer junctions under load underscores the pivotal role of our multilayered architecture in governing the device's pressure-responsive characteristics. Scanning X-ray computed tomography (CT) was used to visualize the 3D structural evolution of the sensor under compression. As shown in Figure 3e, the pristine device exhibits a loosely stacked lamellar structure with distinct interlayer gaps. After compression, CT reconstruction shows a marked reduction in spacing and thickness, indicating interfacial densification and enhanced interlayer contact. These macroscopic observations are consistent with SEM results (Figure 3f), which reveal progressive microchannel closure and interlocking at the electrode–sensing interface. In situ SEM further confirmed this evolution, with cross-sectional images and associated EDS mapping showing gradual interlayer compaction and improved contact under load. For higher-resolution inspection, enlarged SEM views (Figure S34) highlight microchannel closure and tight interlocking between the AgNPs@CPM layer and the MXene electrode during the loading–unloading process.

At the atomic scale, the piezoresistive mechanism at the MXene–AgNP interface was probed through differential charge density ($\Delta\rho$), Bader charge analysis, and density of states (DOS/PDOS) calculations. The $\Delta\rho$ maps (Figure 3g) highlight the strain-dependent redistribution of interfacial charge. At 0% strain, charge accumulation (yellow) and depletion (cyan) remain confined to localized Ag–MXene sites, indicating weak coupling. At 5% strain, these regions expand significantly with stronger electron accumulation on Ag, while at 10% strain, the redistribution becomes continuous and large-scale, signifying maximized interfacial polarization. These results demonstrate that compressive strain effectively promotes interfacial charge delocalization. Bader charge analysis (Figure 3h) quantitatively corroborates this trend. The net charge transfer increases from 1.449 e at 0% strain to 1.737 e at 10% strain (Table S2). Ag and Ti atoms act as electron donors, whereas C and O serve as dominant acceptors. The monotonic increase in net charge transfer confirms that compressive strain systematically enhances interfacial charge transfer. DOS calculations (Figure S35) further support this conclusion, showing a progressive increase in the density of states near the Fermi level, indicating more available conduction channels

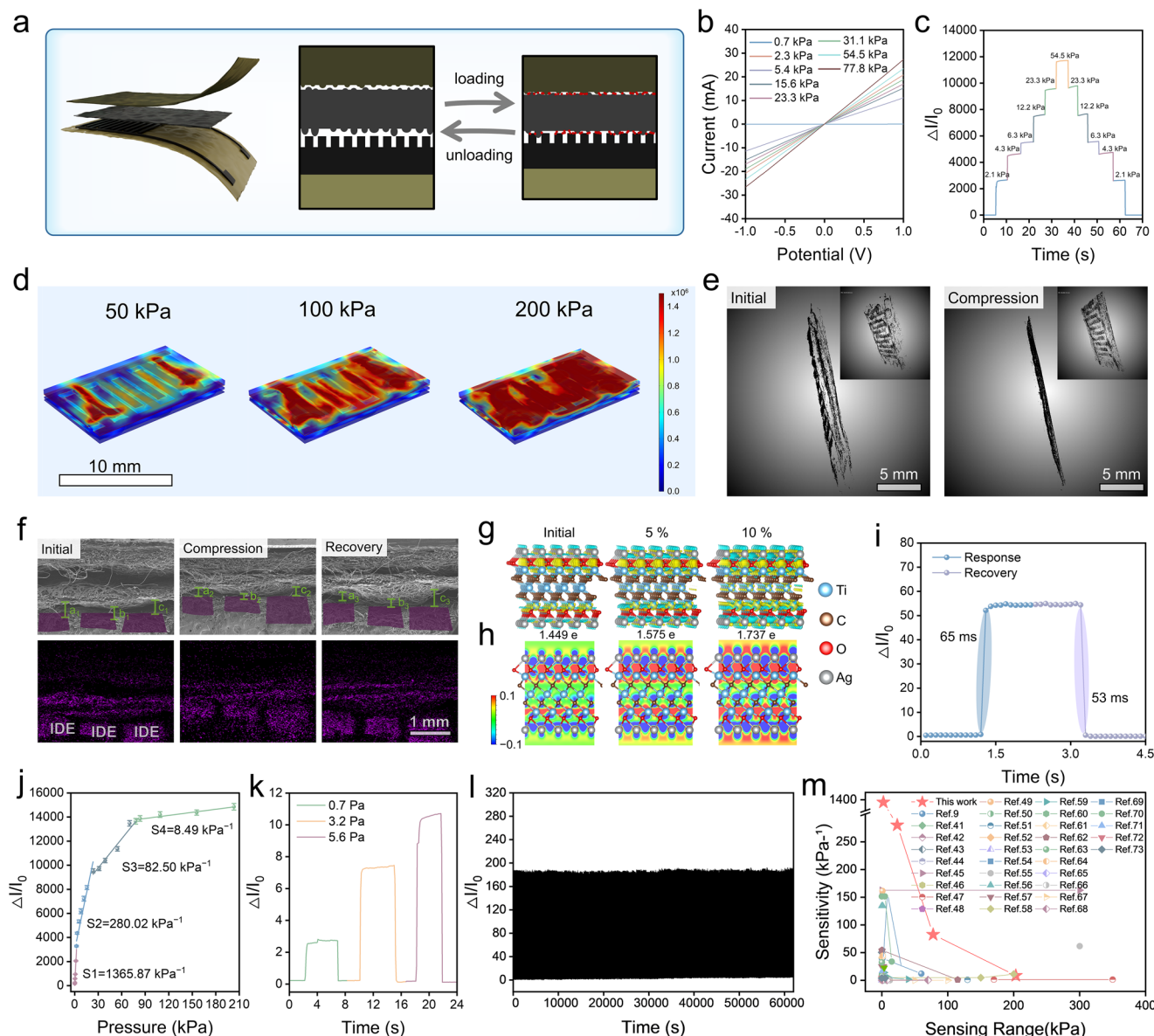


FIGURE 3 | Structural design, simulations, and sensing performance of the all-paper-based pressure sensor. (a) Schematic of the multilayer sensor and pressure-induced conductive pathways. (b) I–V curves under different pressures. (c) Dynamic pressure responses ($\Delta I/I_0$) at various applied pressures. (d) Finite element simulation (0–200 kPa) of stress distribution. (e) Scanning X-ray CT images before and after compression, showing interlayer densification. (f) In situ SEM cross-sections and the corresponding EDS elemental mapping during compression and recovery. (g) Differential charge density ($\Delta\rho$) at 0% (initial), 5%, and 10% compressive strain. (h) Bader charge evolution. (i) Response and recovery times. (j) Pressure–response curve with four linear sensitivity regimes. (k) Detection of ultralow pressures generated by 1, 5, and 8 rice grains, respectively. (l) Durability over 10 000 cycles. (m) Comparison of sensitivity and detection range with reported sensors.

and improved transport capability. PDOS analysis (Figure S36) provides orbital-level insight: the Ag-4d contribution near the Fermi level decreases under strain, reflecting reduced electron occupancy, while Ti-3d states broaden and intensify, demonstrating stronger Ti–Ag hybridization and enriched electronic states. By contrast, the C and O p orbitals remain largely unchanged, consistent with their role in lattice stabilization rather than electronic conduction. Taken together, the $\Delta\rho$, Bader, DOS, and PDOS analyses converge on a unified mechanism: compressive strain drives electron transfer from Ag and Ti to C and O, while simultaneously strengthening Ti–Ag orbital hybridization. The resulting enhancement of electronic states near the Fermi level accounts for the reduced resistance and higher current response

under compression, offering a microscopic origin for the observed piezoresistive behavior.

The conductivity and surface morphology of the sensing layer critically influence pressure-sensing performance. Initial evaluation of three single-layer paper-based sensors made from materials with different surface roughnesses ($R_q = 89.4$, 54.96, and 6.32 μm ; Figure S37) showed that although rougher surfaces improve sensitivity, all configurations suffered from rapid current saturation, limiting the linear detection range to below 70 kPa (Figure S38). To isolate the effect of intrinsic conductivity, we fabricated single-layer sensors (using the optimal material) with varying MXene loadings (Figure S39). Notably, higher

MXene concentrations increased sensitivity but also narrowed the piecewise linear range, inducing saturation beyond 70 kPa. We also systematically studied the effect of AgNP loading on the microstructure and sensing performance of AgNPs@CPM by adjusting the silver nitrate precursor concentration (1–10 wt%). SEM analysis (Figure S40) showed that higher precursor concentrations yielded denser and finer in situ-reduced AgNPs on cellulose fibers, forming a more continuous and interconnected conductive network. This structural evolution directly enhanced the low-pressure sensitivity of the sensor (<10 kPa), which increased dramatically from 65.25 kPa^{-1} (1 wt%) to 164.78 kPa^{-1} (8 wt%). The maximum relative current change ($\Delta I/I_0$) reached 1.49×10^4 at 203.2 kPa for the 10 wt% sample. However, higher AgNP density also caused a slight but observable shift in current saturation toward lower pressures (Figure S41), highlighting a critical trade-off between high sensitivity and operational piecewise linear range. A comparison between self-reduced and commercial AgNPs (Figure S42) revealed that sensors with self-reduced AgNPs exhibited significantly higher sensitivity across the entire pressure range, attributable to stronger interfacial bonding and a more uniform conductive network. SEM imaging combined with EDS mapping (Figure S43) confirmed that self-reduced AgNPs form a continuous, well-distributed metallic layer closely bonded to cellulose fibers, whereas commercial AgNPs tended to aggregate, resulting in isolated conductive domains. This microstructural difference accounts for the superior piezoresistive response of the self-reduced AgNP-based devices. This trade-off motivated our stepwise three-layer gradient design. By combining a high-conductivity AgNPs@CPM sublayer and a low-conductivity AgNPs@CPM-Hyd outer layer above the MXene interdigitated electrode, we overcome the sensitivity–detection range compromise, achieving both an extended detection range and enhanced sensitivity (Figure S44).

Furthermore, the sensor demonstrates an ultra-fast response time (65 ms) and recovery time (53 ms), comparable to human skin response, making it highly suitable for monitoring human motion (Figure 3i). Sensitivity, a key performance parameter, is calculated as $S = (\Delta I/I_0)/\Delta P$, where ΔI is the current change, I_0 the initial current, and ΔP the pressure change. Figure 3j shows the sensitivity curve of the all-paper-based sensor, which exhibits four linear regions: 1365.87 kPa^{-1} (0.7 Pa–2.334 kPa), 280.02 kPa^{-1} (2.334–23.34 kPa), 82.50 kPa^{-1} (23.34–77.8 kPa), and 8.49 kPa^{-1} (77.8–203.2 kPa). Each region exhibits high linearity, with coefficients of determination (R^2) of 0.995, 0.943, 0.971, and 0.941, respectively. The step-wise sensitivity regions (S1–S4) originate from the intrinsic “contact-jumping” behavior of the hierarchical cellulose network. Unlike elastomeric substrates (PDMS) that deform smoothly and continuously, the semi-rigid and highly rough cellulose fibers resist gradual compression. When the applied local pressure exceeds a critical threshold, the rigid structural skeleton undergoes abrupt mechanical buckling or collapse. Consequently, the contact configuration transitions instantaneously from sparse point contacts to extensive line or area contacts. This effect is further amplified by the hierarchical architecture of the paper (from macroscopic fibers down to nanoscale fibrils), creating a cascade of sudden contact events. Operating near the electrical percolation threshold, these sudden mechanical slippages trigger a sharp, discontinuous surge in parallel conductive pathways. Normally, this contact-jumping mechanism leads to rapid current saturation within a narrow

low-pressure window, as confirmed by our single-layer sensor which saturates prematurely at approximately 70 kPa. However, the step-wise conductivity-gradient trilayer architecture proposed herein acts as a current-limiting buffer, systematically distributing these intense contact-jumping events across sequential stages, thereby extending the effective piecewise-linear sensing range to 0.7 Pa–203.2 kPa. Specifically, the dynamic evolution across these four stages can be strictly correlated with the progressive mechanical deformation and interfacial evolution of the hierarchical porous matrix under compression. In the S1 region (ultra-low pressure), only the highest surface asperities establish initial discrete contacts, abruptly forming highly efficient shortest conductive pathways and resulting in an extremely high sensitivity. As the pressure increases to the S2 region, the large pores within the fibrous network undergo elastic closure, promoting extensive lateral contacts and structural buckling among adjacent fibers. Entering the S3 region, the cellulose matrix experiences bulk densification, and the internal conductive network achieves comprehensive percolation; consequently, the marginal contribution of newly formed pathways to the overall conductivity decreases, leading to a moderated sensitivity. Finally, in the S4 region (high pressure), the compressible macro/micro-pores are fully depleted, rendering further mechanical deformation exceedingly difficult. In this stage, the variation in resistance primarily relies on the intrinsic piezoresistive effect of the highly compacted interfaces rather than the creation of new contact areas, where compressive strain systematically drives interfacial charge delocalization and electron transfer to sustain the piezoresistive response. To assess environmental robustness, the sensor was tested under varying temperatures (6°C – 70°C). As shown in Figure S45, it exhibited stable and repeatable responses with only minor attenuation at high temperatures, confirming excellent thermal stability. Long-term storage tests under ambient conditions (Figure S46) showed that the device retained over 95% of its initial sensitivity after 14 days, demonstrating minimal degradation and reliable durability. To directly probe the oxidative stability of the conductive network, the normalized resistance of the encapsulated and unencapsulated MXene layers was tracked over 28 days: the SL-Colophony-encapsulated network remained essentially unchanged, whereas the unencapsulated counterpart degraded markedly, especially under high humidity (Figure S47), directly confirming that the encapsulation suppresses MXene oxidation. Furthermore, systematic evaluations under extreme environmental conditions were conducted to validate the practical reliability of the device. Initially, the pressure-sensing performance was evaluated across varying relative humidity levels (from $45 \pm 5\%$ RH to $97 \pm 1\%$ RH); the sensor exhibited highly consistent sensitivity, confirming that the SL-Colophony hydrophobic layer effectively prevents immediate moisture interference (Figure S48). To further assess prolonged environmental durability, the sensor was stored at the highest tested humidity ($97 \pm 1\%$ RH) for 28 days, retaining over 92% of its initial sensitivity (Figure S49). To simulate realistic on-skin operating conditions, the sensor was subjected to artificial sweat (NaCl solution) immersion for 3 and 12 h. Subsequent testing demonstrated no performance decay; rather, a slight sensitivity enhancement was observed, which can be attributed to ion-assisted conduction and optimized interfacial contact via mild fiber swelling (Figure S50). Together, these comprehensive evaluations verify that the sensor possesses strong environmental robustness, ensuring reliable long-term functionality in sweat-intensive or highly humid wearable

scenarios. Notably, the sensor can detect ultra-low pressures down to 0.7 Pa (Figure 3k). Moreover, over 10 000 cycles, the current response remained rapid and stable (Figure 3l), with negligible fluctuations in I–T curves, indicating strong long-term durability. Although slight sensitivity attenuation occurred in later cycles, overall performance remained high, underscoring the strong practical potential of the sensor. Moreover, the sensor demonstrates excellent resistance to interlayer delamination during prolonged deformation, driven by the microscale mechanical interlocking of the rough cellulose fibers. Quantitative thickness measurements before and after 10 000 compression cycles (Table S3) confirm that the original layer thicknesses are well-preserved with high retention rates, indicating the absence of severe structural collapse or macroscopic separation. Beyond single-device performance, the fabrication process is highly reproducible: five independently prepared sensors exhibited consistent multi-stage sensitivities (S1–S4) with a low relative standard deviation of $\leq 4.0\%$ across all four stages (Figure S51). Compared to other pressure sensors (Figure 3m [9, 40–72], Table S4), our sensor exhibits high sensitivity, low detection limits, and strong durability, while maintaining competitive advantages in detection range and response time. Consequently, the specific operating limits of the device are strictly defined: it sustains stable piecewise-linear sensing up to a mechanical load of 203.2 kPa, maintains reliable signal output across 6°C – 70°C , and tolerates extreme moisture up to direct liquid water exposure (Table S5).

2.4 | Real-Time Applications of Multifunctional Paper-Based Sensor Device

This paper-based sensor device also demonstrates practical utility in wearable health monitoring and human–machine interfaces. Multidimensional biomechanical tests (Figure S52) were systematically performed on the AgNPs@CPM sensor. The ultraflexible all-cellulose substrate affords intimate skin conformability, enabling multimodal, high-fidelity, and noninvasive physiological sensing. Upon high-frequency fingertip tapping, the device produces sharp transient current spikes with millisecond-scale response and high sensitivity (Figure 4a); Video S5 directly records these spikes from an electrochemical workstation, while Video S6 visualizes the concomitant LED brightness modulation driven by the sensor under incremental loads. During stepwise finger-joint bending, distinct, reproducible signal increments corresponding to increasing bending angles are resolved (Figure S53). Meanwhile, the dynamic signal evolution is also captured in Video S7, which illustrates stable and repeatable current responses when the sensor is connected to an electrochemical workstation during continuous bending–straightening cycles. Under large deformations, the device maintains robust cyclic durability, as evidenced by reliable signal output during repeated knee-bending cycles (Figure S54).

Beyond mechanical sensing, the device functions effectively in acoustic recognition when attached to the larynx (Figure 4b), where vocal cord vibrations are converted into discernible current signals, offering a promising platform for non-contact voice interaction. Moreover, the sensor resolves subtle radial-artery pulse waveforms, clearly identifying percussion (P), tidal (T), and dicrotic (D) waves (Figure 4c). Following exercise, heart rate increased from 73 to 109 bpm, confirming the capability of

the sensor for dynamic physiological tracking (Figure 4d). The device further demonstrates strong environmental adaptability, particularly in submerged environments, owing to the stable conductive network of the MXene/AgNPs heterojunction and a highly hydrophobic encapsulation layer. As shown in Figure S55, the sensor shows a stable, fully recoverable electrical response to sequential surface water droplets, confirming strong resistance to water interference. Even when fully submerged, it reliably detects finger touch (Figure 4e), overcoming a key limitation of conventional flexible sensors in underwater operation. This capability underscores its potential for underwater health monitoring and interactive systems.

For humidity sensing, the bare hydrophilic AgNPs@CPM layer serves as the sensing unit, spatially decoupled from the hydrophobically encapsulated pressure device so that the two functions do not interfere (Supplementary Note 6, Supporting Information). This AgNPs@CPM layer exhibits strong humidity sensitivity due to the rich terminal functional groups ($-\text{OH}$, $-\text{O}$, and $-\text{F}$) of MXene, which facilitate moisture interaction and enhance electron transport across interlayer potential barriers. This mechanism dynamically modulates electrical resistance via a reversible adsorption–desorption process of water molecules. When exposed to salt solutions across a range of relative humidity (RH) values, the relative current change ($-\Delta I/I_0$) of the sensor increases progressively from 11% to 97% RH, reaching a maximum of 92.84% (Figure 4f). We further explored respiratory monitoring by positioning the sensor near the mouth of a volunteer, where it effectively distinguished breathing states through humidity-induced resistance changes (Figure 4g). During inhalation, elevated moisture led to higher resistance, while exhalation resulted in lower humidity and decreased resistance. Under normal conditions, the respiratory rate was 20 breaths min^{-1} , within the healthy range; rapid breathing increased the breathing frequency, whereas deep breathing reduced the rate to 15 breaths min^{-1} but amplified humidity fluctuations, further confirming high precision in respiratory tracking. To evaluate non-contact environmental humidity sensing, we assessed the response of the sensor to a wet fingertip at varying distances. As shown in Figure 4h, as the distance increased from 1 to 5 mm, the resistance displayed stepwise variations, highlighting potential applications in non-contact human–machine interaction, real-time environmental monitoring, and intelligent control systems.

In vitro cytotoxicity tests evaluated the biosafety of CPM, CP, and blank controls. Live/dead staining (Figure 4i; Figure S56) revealed only a few dead cells after 1 and 3 days, confirming excellent biocompatibility and low cytotoxicity. L929 fibroblast cells cultured on sample surfaces showed proliferation comparable to the control via CCK-8 assay (Figure 4j). Skin compatibility tests (Figure 4k) showed no visible irritation or discoloration after 1 day of wear, confirming the excellent biocompatibility and comfort of the cellulose-based design. In contrast, sensors encapsulated with PI or PET films caused noticeable skin redness within 6 h, which worsened after 12 h and persisted for 1 day, highlighting the superior skin compatibility of our device. While ISO 10993–5 cytotoxicity and preliminary 24 h patch tests confirm excellent immediate biosafety, comprehensive in vivo evaluations—such as large-cohort skin irritation and ISO 10993–10 sensitization tests—have not yet been performed. Although individual components (MXene and AgNPs) are safe

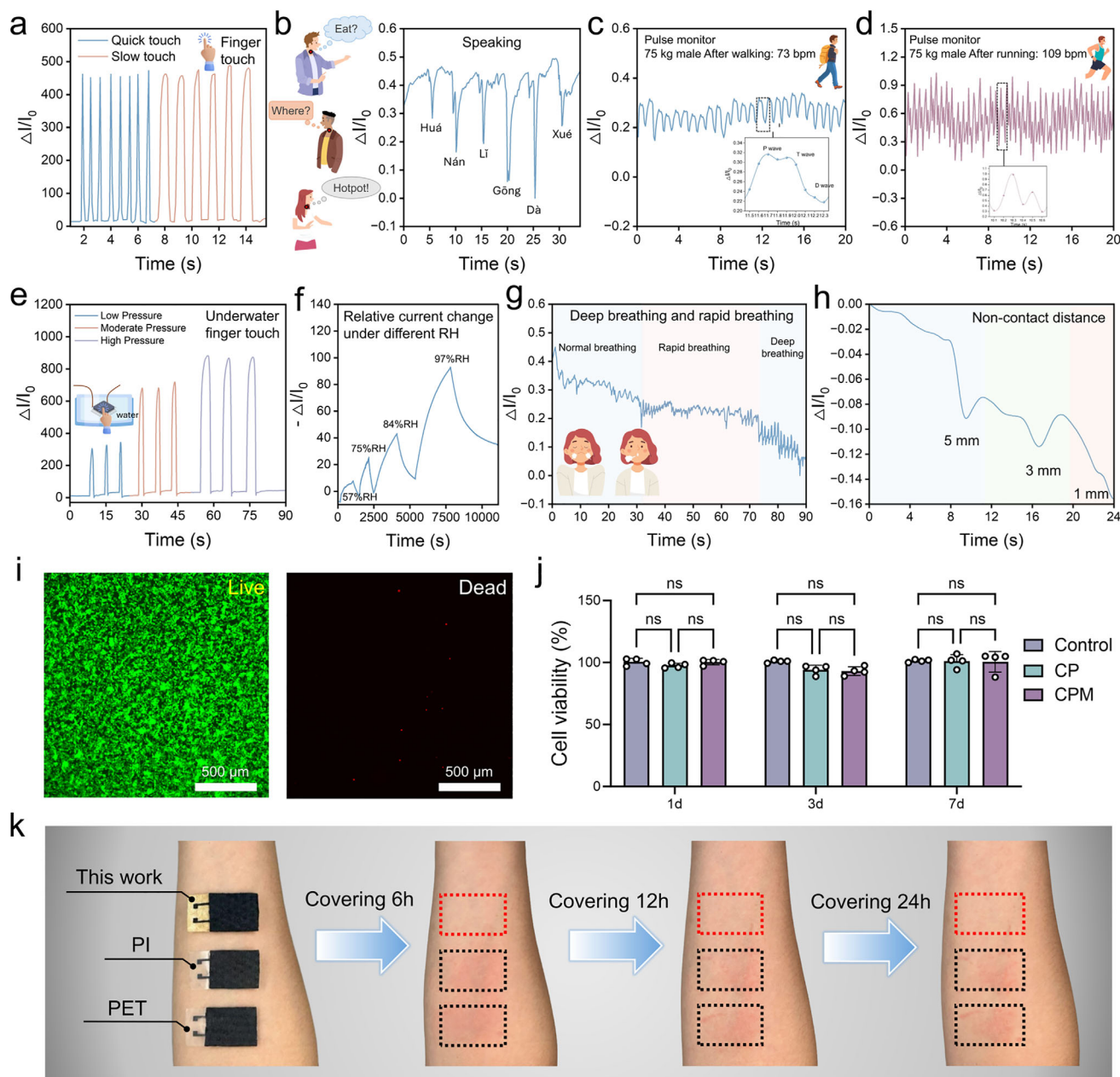


FIGURE 4 | Multidimensional evaluation and practical applications of the sensor. (a) Electrical responses under quick touch and slow touch stimuli. (b) Voice detection when the sensor is attached to the larynx, showing signal variations during speaking. (c) Radial pulse monitoring with characteristic waveform features. (d) Pulse signals measured before and after exercise. Insets show enlarged waveform details. (e) Signal response to finger touch under water. (f) Relative current change ($-\Delta I/I_0$) of the sensor under different relative humidity conditions. (g) Signal changes during normal, rapid, and deep breathing. (h) Non-contact sensing response at different finger-to-sensor distances. (i) Live/dead fluorescence staining images of cells cultured with CPM. (j) Cell viability of Control, CP and CPM groups after 1, 3 and 7 days. (k) Photographs showing skin attachment of the sensor for 6, 12 and 24 h.

at low concentrations, executing these standardized preclinical protocols remains a necessary future step before broad clinical deployment. A balanced comparison with polymer-based flexible sensors helps position this work. Elastomer-based sensors (PDMS or Ecoflex) offer superior stretchability, tear resistance, and environmental stability, while biodegradable-polymer sensors are mechanically well established. However, their dense films inherently limit breathability and long-term on-skin comfort. In contrast, our all-cellulose platform trades some ultimate stretchability for the breathability, thermophysiological comfort,

and partial biodegradability essential to continuous on-skin monitoring, while still delivering competitive multifunctional sensing. This positions the device as a skin-friendly, sustainable alternative particularly suited to daily wearable biomonitoring rather than extreme-deformation scenarios.

Beyond sensing, the device was integrated with a microcontroller (Arduino UNO R3) and a Bluetooth module (HC-05) to establish a wireless real-time monitoring system. The physical assembly and wiring of this system are shown in Figure S57, while

its operational principle and signal transmission pathway are schematically illustrated in Figure S58. This integrated system successfully enables real-time detection of sensor deformation during both rapid and slow fingertip motions (Video S8), highlighting its strong potential for next-generation wearable and interactive technologies.

2.5 | Electromagnetic Shielding Performance and Mechanism

The stepwise conductivity-gradient architecture developed here enables the sensor to achieve both a broad detection range and excellent electromagnetic interference (EMI) shielding performance (Figure S59). The multiscale porosity ensures compressibility for high-sensitivity pressure response, while the MXene gradient maintains a continuous conductive network for efficient EMI shielding. SEM images (Figure S60) show that the MXene layer remains intact after repeated compression, confirming the mechanical stability of the conductive network. The AgNPs@CPM-based all-paper sensor demonstrates outstanding EMI shielding performance, achieved via a multilayer composite structure that employs a reflection-dominated yet absorption-enhanced synergistic mechanism for efficient electromagnetic protection (Figure 5a,b). The shielding initiates at the bottom MXene interdigital electrode layer, where the conductive interdigital pattern reflects part of the incident electromagnetic waves through free electron oscillation, establishing the first defense barrier. The adjacent non-conductive CP substrate allows residual electromagnetic waves to penetrate into the middle and top layers, enabling selective electromagnetic energy regulation. Within the AgNPs@CPM composite matrix of these upper layers, the transmitted waves experience multiple dissipation pathways, including ohmic losses from the high-density free carriers in silver nanoparticles that convert electromagnetic energy into Joule heat, charge accumulation at the AgNPs–MXene heterojunction induces a spatial polarization field that intensifies dielectric losses via interfacial polarization. Moreover, the micro-capacitor effect of the nanoparticles coupled with the hydrophobic surface roughness induces multiple internal reflections and scattering, substantially extending the electromagnetic wave propagation path and thereby enhancing energy dissipation efficiency [73]. Ultimately, the cooperative interaction between reflection/transmission modulation at the bottom layer and absorption/scattering in the middle and top layers results in a three-layer sensor with a shielding effectiveness (SET) of 106 dB in the X-band (8.2–12.4 GHz), corresponding to blocking over 99.999999% of the incident electromagnetic power.

The electrical conductivity of AgNPs@CPM was systematically tuned by adjusting the silver precursor concentration, leading to a progressive enhancement in EMI shielding performance. As shown in Figure 5c, the shielding effectiveness (SE) in the X-band increases steadily from approximately 8.2 dB for pristine CPM to about 46 dB for AgNPs-10@CPM with the highest silver loading. This dose-dependent enhancement indicates that silver nanoparticle incorporation not only fortifies the conductive network but also enhances interfacial polarization, synergistically promoting efficient electromagnetic energy dissipation. A detailed breakdown of shielding components, absorption effectiveness (SEA), reflection effectiveness (SER), and total

shielding effectiveness (SET), presented in Figure 5d reveals SEA overwhelmingly dominates the shielding performance across all samples. SEA rises sharply from 0.37 dB for pristine CP to 35.13 dB for AgNPs-10@CPM, representing nearly a 100-fold increase in absorption capacity, whereas SER exhibits a more moderate increase from 0.04 to 10.96 dB within the same range. The combined effect yields a maximum SET of approximately 46.1 dB. This pronounced absorption dominance highlights the pivotal role of silver nanoparticles in enhancing internal electromagnetic energy dissipation, which is essential for effectively minimizing secondary electromagnetic pollution caused by reflected waves and thus improves overall shielding efficiency.

Power coefficient analysis in Figure 5e indicates that the reflected power ratio (R) consistently exceeds the absorbed power ratio (A) for all AgNP-loaded samples, especially in highly conductive AgNPs@CPM composites. R increases from ~0.30 in pristine CPM to over 0.91 for AgNPs-10@CPM, while A remains below 0.50 and decreases to ~0.08 in the highest silver-content sample. This apparent contradiction to SEA dominance arises because SEA accounts for total electromagnetic absorption after multiple internal reflections (reflection–absorption coupling), while R reflects only initial surface reflection [74]. The strong impedance mismatch between free space and the conductive layer in AgNPs@CPM leads to high surface reflection, resulting in large R values. The residual transmitted waves undergo multiple internal reflections and scattering, generating effective absorption captured by SEA. Thus, although power coefficients reveal a reflection-dominated immediate power loss, the synergistic effect of internal multiple reflections and absorption underpins the high overall shielding effectiveness, ensuring optimized EMI shielding.

Further optimization is achieved through the multilayer structural design of the sensor (Figure 5f). As the number of functional layers increases from one to three—corresponding to the complete trilayer sensor architecture (top hydrophobic buffering layer, intermediate AgNPs@CPM sensing layer, and bottom MXene IDE)—the EMI SE increases progressively to a maximum of 106 dB. This demonstrates the synergistic shielding contribution of each functional layer within the integrated device, as the hierarchical conductive interfaces induce multiple reflection and absorption of electromagnetic waves. Notably, SER remains stable (Figure 5g), indicating that surface reflection is independent of layer count, whereas SEA increases significantly due to multiple reflection-absorption cycles induced by multilayer heterogeneous interfaces. The near-constant values of transmission (T), reflection (R), and absorption (A) (Figure 5h) confirm the consistency of the shielding mechanism across different layer numbers. The sensor exhibits strong mechanical durability: after 500 bending and compression cycles, the EMI SE curves remain nearly unchanged across the X-band (Figures S61 and S62), evidencing stable shielding under repeated mechanical stress. This durability stems from the structurally resilient 3D conductive network that maintains electrical integrity during deformation. Additionally, the EMI shielding remains stable after 30 min exposure to extreme temperatures, liquid nitrogen (−196°C), and tube furnace (100°C) (Figure S63), demonstrating excellent thermal and mechanical robustness. To further benchmark the EMI shielding performance, Table S6 compares our AgNPs@CPM sensor with representative paper-based, MXene-based, and composite

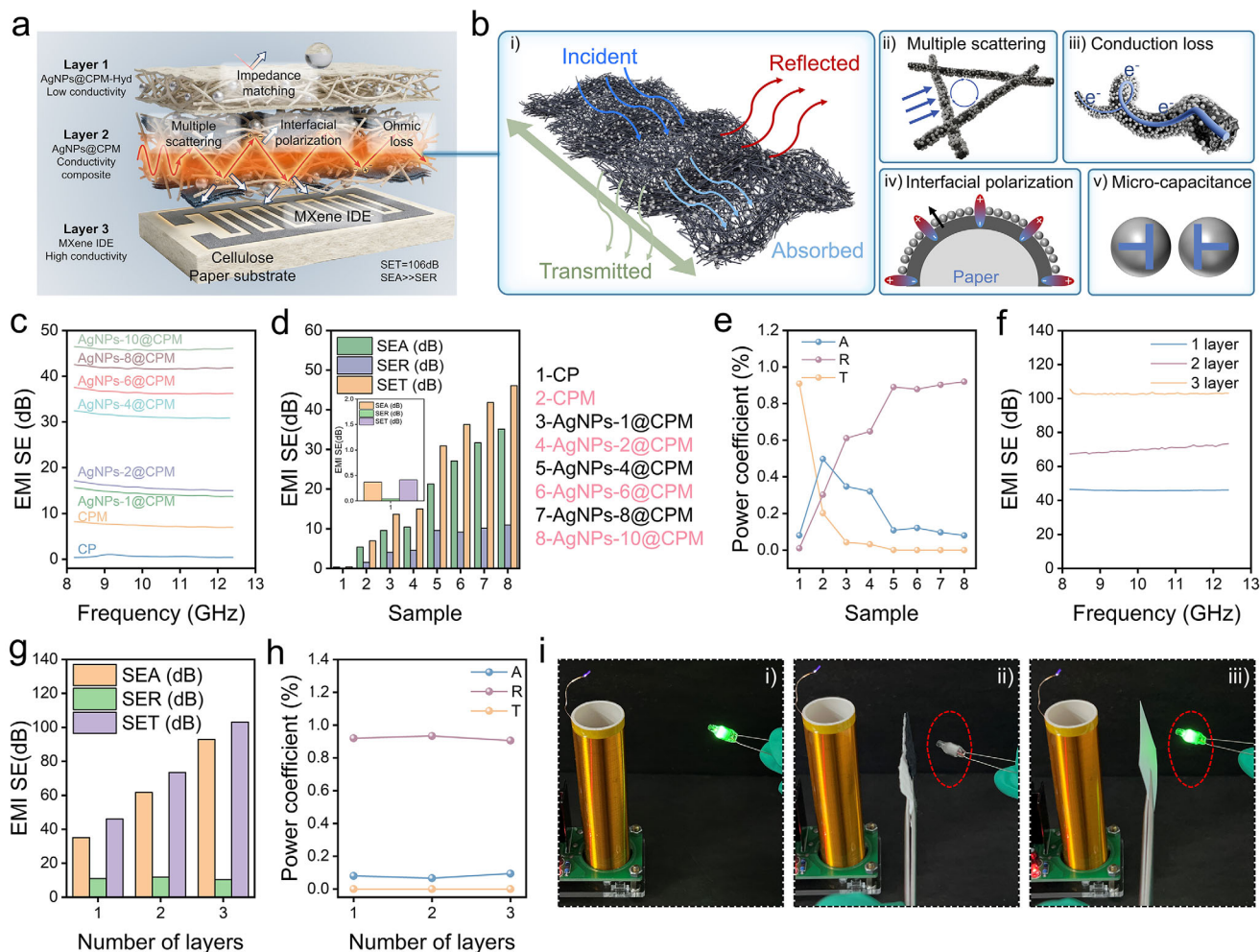


FIGURE 5 | EMI shielding performance of the AgNPs@CPM-based all-paper sensor. (a) Schematic illustration of the multilayer paper-based shielding structure. (b) Proposed electromagnetic shielding mechanism involving reflection, absorption and multiple internal scattering, together with conduction loss, interfacial polarization and micro-capacitance effects. (c) EMI shielding effectiveness (SE) of CPM and AgNPs@CPM in the X-band. (d) Total shielding effectiveness (SET), absorption contribution (SEA) and reflection contribution (SER) for samples with different AgNP loadings. (e) Power coefficients of reflection (R), absorption (A) and transmission (T) for representative samples. (f) Frequency-dependent EMI SE of structures with 1, 2 and 3 layers. (g) SET, SEA and SER as a function of layer number. (h) Power coefficients (R, A and T) as a function of layer number. (i) Photographs of EMI shielding performance in a Tesla coil wireless transmission setup: blank, AgNPs@CPM sensor and regular paper.

shielding materials reported in recent literature. The maximum SET of 106 dB achieved by the three-layer architecture far exceeds that of most counterparts, even those fabricated through more elaborate processes such as high-temperature sintering, vacuum-assisted assembly, or polymer encapsulation. This advantage underscores both the scalability and practical promise of the all-paper AgNPs@CPM sensor for next-generation electromagnetic protection applications. The EMI shielding capability is further validated dynamically by a Tesla coil test. Without the sensor, the radio frequency (RF) signal from the Tesla coil fully illuminates the fluorescent diode (Figure 5i). Placing the sensor between coil and diode extinguishes the light, confirming effective blocking of high-frequency electromagnetic waves, whereas ordinary paper fails to shield the signal. Additional demonstrations, including contactless LED activation (Video S9) and spark discharge suppression (Video S10), further corroborate the superior shielding performance of the sensor. The high-frequency EMI shielding of the AgNPs@CPM sensor renders it promising for applications in wireless communication interference suppres-

sion, aerospace electromagnetic protection, and medical device safeguarding.

3 | Discussions

In this study, we present a fully cellulose-based pressure sensor that leverages a stepwise conductivity-gradient architecture to overcome the intrinsic sensitivity-detection range trade-off that limits conventional resistive paper devices. By integrating MXene nanosheets with in situ reduced Ag nanoparticles within hierarchical cellulose networks, the sensor establishes a strain-activated piezoresistive pathway that enables progressive modulation of charge transport under compression. Together with the mechanically compliant top sensing layer and the high-conductivity transition layer, this cascaded design yields ultrahigh sensitivity (1365.87 kPa^{-1}), a broad detection range of 0.7 Pa–203.2 kPa covered by a four-stage piecewise-linear response ($R^2 = 0.941\text{--}0.995$), a detection limit of 0.7 Pa, and excellent durability over 10 000

cycles. DFT analyses further reveal that compressive strain promotes Ag–MXene interfacial charge delocalization and enhances electronic hybridization, providing a mechanistic basis for the observed high-performance piezoresistive behavior. Beyond pressure sensing, the interconnected MXene–AgNP networks deliver outstanding EMI shielding effectiveness (106 dB) and maintain intrinsic breathability and environmental robustness through cellulose's porous framework and hydrophobic functionalization. Demonstrations in physiological signal monitoring and motion analysis validate the sensor's capability for precise, real-time detection of subtle biomechanical activities. Owing to its highly sustainable material basis, partial biodegradability rooted in the cellulose matrix, scalability, and multifunctional integration, this work provides a sustainable, high-performance platform for wearable electronics, with potential applications in healthcare monitoring, human–machine interfaces, and soft robotics. It should nonetheless be acknowledged that more comprehensive and standardized biocompatibility evaluations are still needed to fully establish the long-term on-skin safety of the device, and that the non-biodegradable silver and MXene constituents call for responsible material recovery and end-of-life management to fully realize the environmental sustainability of this cellulose-based platform.

4 | Experimental Section

A detailed description of materials, fabrication procedures, characterization methods, and biocompatibility evaluations is provided in the Supplementary Information.

Consent

All participants in the human physiological signal monitoring experiments were the authors of this article, who performed the measurements noninvasively and provided informed consent for their participation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: adfm77836-sup-0001-SupMat.docx.

Supporting File 2: adfm77836-sup-0002-VideoS1.mp4.

Supporting File 3: adfm77836-sup-0003-VideoS2.mp4.

Supporting File 4: adfm77836-sup-0004-VideoS3.mp4.

Supporting File 5: adfm77836-sup-0005-VideoS4.avi.

Supporting File 6: adfm77836-sup-0006-VideoS5.mp4.

Supporting File 7: adfm77836-sup-0007-VideoS6.mp4.

Supporting File 8: adfm77836-sup-0008-VideoS7.mp4.

Supporting File 9: adfm77836-sup-0009-VideoS8.mp4.

Supporting File 10: adfm77836-sup-0010-VideoS9.mp4.

Supporting File 11: adfm77836-sup-0011-VideoS10.mp4.