ADVANCED CELLULOSE/FERROELECTRIC - BASED MATERIALS FOR FLEXIBLE ELECTRONICS: A SHORT REVIEW

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Abstract. Flexible electronics have been becoming essential for modern technology due to their unique electromechanical properties including flexibility, stretchability, and conformability that enable intimate interfaces with curved, dynamic, and biocompatible surfaces. This trend has driven the rapid development of novel materials with increasingly stringent performance requirements. Although cellulose and ferroelectrics have individually established their positions in electronic technologies, the integration of these components within a single material system has gained significant research momentum in recent years, spanning less than a decade. Although this is a relatively specialized class of materials with limited publications, its applications are remarkably broad across modern technological fields, particularly in healthcare and soft robotics. Thus, the present review aims to provide researchers with a comprehensive overview of cellulose/ferroelectric-based materials in the recent decade, summarizing their properties, applications, fabrication methods, advantages and limitations, as well as prospective directions for future research. This overview is of significant importance for the development of core technologies in the field of smart electronics.

Keywords. Cellulose, ferroelectrics, cellulose/ferroelectric – based materials, flexible electronics.

1 INTRODUCTION

The flexible electronics market is predicted to reach $74 billion by 2030 spreading over state-of-the-art applications in healthcare, consumer electronics, energy harvesting, and robotics [1]. Specifically, in robotics, the near-term goal of humanoids equipped with full-body flexible e-skin remains a driving vision. In healthcare, flexible wearable sensors have progressed from laboratory demonstrations to human-validated platforms capable of real-time molecular monitoring in sweat, saliva, and other body fluids. Over time, its advancement has been driven in parallel with the evolution of materials toward lower cost while offering enhanced and multifunctional performance.

Cellulose has gained significant attention in electronics due to its abundance, biodegradability, mechanical flexibility, and tunable surface chemistry, enabling its use as a sustainable substrate, dielectric layer, or scaffold for functional materials [2]. Its porous structure and abundant hydroxyl groups also facilitate surface modification and strong interfacial interactions with functional fillers. These features make cellulose an ideal matrix for composite materials designed for sensors, energy harvesters, and dielectric devices. As a result, cellulose-based material systems represent a promising pathway toward environmentally friendly and mechanically compliant electronic platforms. Meanwhile, ferroelectrics by themselves are essential with their spontaneous and switchable polarization [3]. The intrinsic ferroelectricity enable their use in non-volatile memory devices, capacitors, actuators, and electrocaloric systems. Especially, ferroelectrics have attracted increasing attention in the field of flexible electronics, where mechanical compliance and functional responsiveness must coexist. Their strong electromechanical coupling makes them particularly suitable for flexible sensors, piezoelectric nanogenerators, and self-powered wearable devices [3]. Furthermore, ferroelectric materials can convert mechanical energy into electrical signals with high sensitivity, which is essential for pressure and strain monitoring applications. Therefore, integrating ferroelectrics into flexible and lightweight platforms represents a promising strategy for the development of next-generation smart and adaptive electronic systems.

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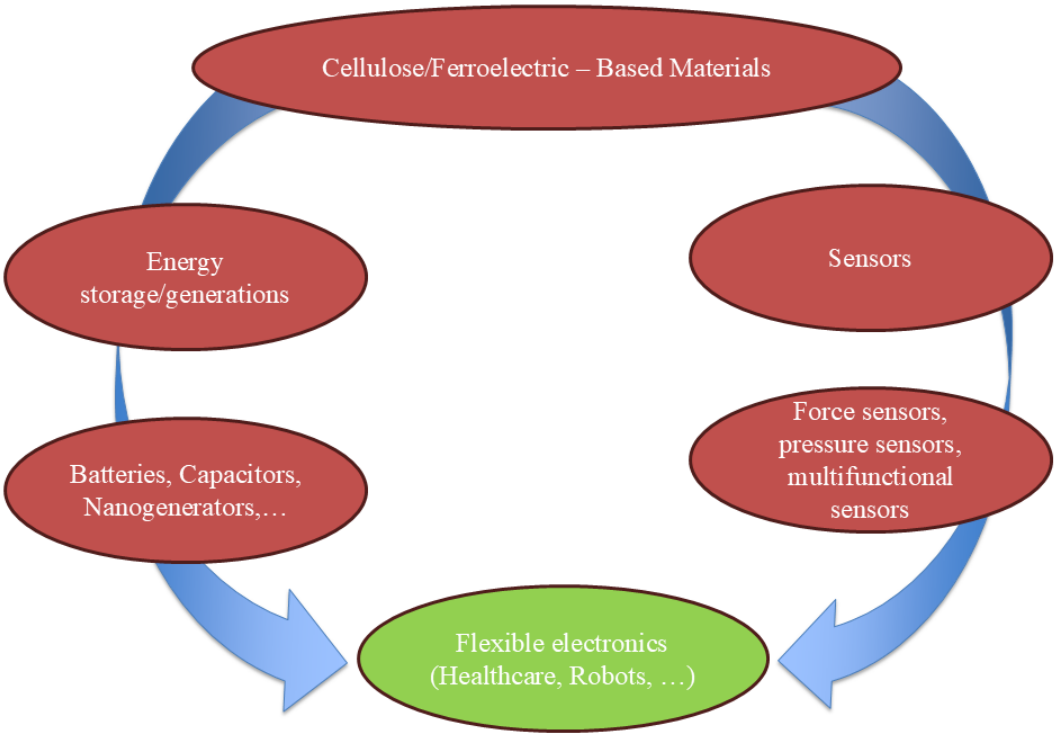


Figure 1: Scheme for applications of cellulose/ferroelectric – based materials

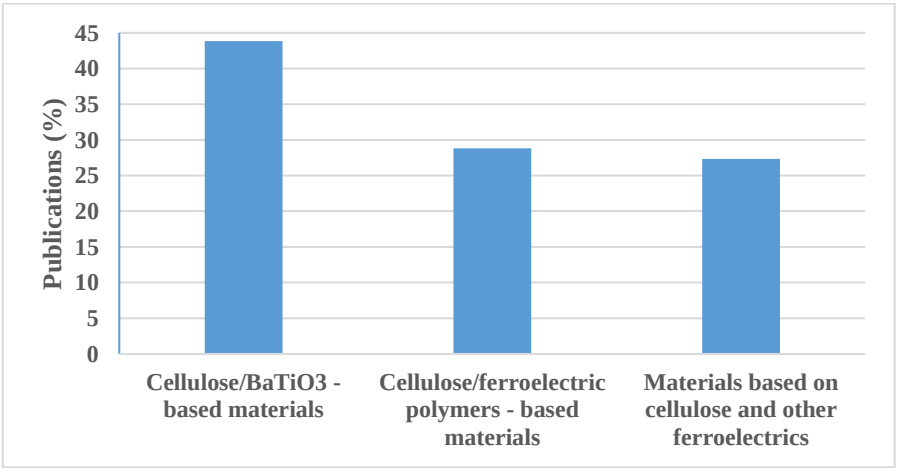


Figure 2: Distribution of publications on flexible cellulose/ferroelectric - based materials during the period 2016 – 2026.

Over the recent decade, the integration of cellulose and ferroelectrics within a single material system has achieved notable success. Applications of cellulose/ferroelectric-based materials are primarily concentrated in two main directions: energy generation and storage, and flexible sensing systems [4-57]. These components are widely integrated into devices for healthcare monitoring and modern soft robotics. Specifically, these applications extend from wearable biomedical sensing (e.g., plantar pressure monitoring and robotic sensory skins) to mechanical energy harvesting and power generation, passive energy storage devices such as capacitors and solar cell components, as well as environmental gas sensing applications. A detail analysis will be given in this paper.

Although cellulose/ferroelectric-based materials have been widely applied in various modern scientific and technological fields over the past decade, the number of scientific publications on this class of materials remains relatively limited [4-57]. Existing studies are predominantly concentrated in three main directions (Figure 2): (i) flexible materials developed based on cellulose and $BaTiO_3$ [4-28] (ii) composites combining

cellulose with ferroelectric polymers, primarily poly(vinylidene difluoride) (PVDF) [5, 13, 19, 29-42], and (iii) other systems derived from cellulose integrated with alternative ferroelectric materials [43-57]. It can be seen in Figure 2 that the cellulose/$BaTiO_3$ – based materials are accounted for the majority of publications and also have the widest application range, followed by cellulose/ferroelectric polymers- and cellulose/other ferroelectrics-based systems. This review therefore focuses on these three material branches, providing a systematic analysis of their properties, applications, fabrication methods, advantages and limitations, as well as prospective directions for future research.

A systematic literature search was conducted using four major scientific databases: Web of Science, Scopus, Google Scholar, and ScienceDirect. The data was collected from January 1st to March 30th in 2026. Relevant publications were identified using keywords and combinations of terms directly related to the main topics covered in this review. The retrieved publications were screened according to their relevance to the scope and objectives of the review. Studies that directly addressed the investigated materials, their flexibility, preparation methods, their composition, and related applications were selected for further analysis, whereas publications with limited relevance to the main topic were excluded. The collected data were organized and evaluated to identify general trend and remaining challenges in the fields.

2 CELLULOSE/BATIO3 – BASED MATERIALS

Cellulose/$BaTiO_3$ – based materials have emerged as a versatile material platform for flexible electronics, spanning energy harvesting, energy storage, and sensing applications (Table 1). These material systems employ diverse cellulose types paired with $BaTiO_3$ loadings along with other additional ingredients. TEMPO oxidation form of cellulose is a particularly common surface treatment that introduces carboxylate groups on the cellulose surface, enhancing compatibility with $BaTiO_3$ nanoparticles [10, 13, 17, 19, 24] (Figure 3a). Next, modified cellulose derivatives including cellulose acetate [7, 8] (Figure 3b), trilayer cellulosic paper [6, 12] (Figure 3c), carboxymethyl nanocellulose [25, 26], cellulose nanofibers [5, 9] (Figure 3e) and cyanoethyl cellulose [18, 27, 28] were also employed (Figure 3f), each conferring specific dielectric or processing advantages. Besides, regenerated cellulose dissolved in NaOH/urea systems is another prominent approach [20, 23] (Figure 3g). Although less frequently utilized, other kinds of cellulose such as 3D cellulose scaffold [14] (Figure 3h), cellulose aerogel [22] (Figure 3i), cotton-sourced cellulose nanofibers [15], cellulose nanofibrils [21] (Figure 3j), natural cellulose [4] (Figure 3k), hydroxypropyl cellulose [16] (Figure 3l), bacterial cellulose [58] (Figure 3m) and wood cellulose fibers [59] (Figure 3n) have nevertheless established a strong and distinctive impact on practical applications. Regarding $BaTiO_3$, it is predominantly used in nanoparticle form with diameters typically ranging from 50 to 300 nm with various content up to 90 wt% (Table 1). In some cases, surface modification of $BaTiO_3$ can be applied to improve filler-matrix compatibility and dispersion. For instance, polydopamine (PDA) coating is the most common approach [5, 7, 8, 15, 20]. At the same time, silane coupling agents were used for surface modification of $BaTiO_3$ nanoparticles in a PVDF ternary system [19]. Additionally, MoS_2 nanosheets [17], TiO_2 shells forming core-shell $BaTiO_3$@TiO_2 structures [9], antimony tin oxide (ATO) [27], and carbonized polymer dots (CPDs) [7] were also reported. Solution casting and blending represent the simplest and most widely adopted fabrication routes. Several studies explicitly highlight their approaches as facile and scalable [14, 17, 58].

Table 1: Composition and applications of cellulose/$BaTiO_3$-based materials

Cellulose Type	**$BaTiO_3$ Content**	**Additional Components**	**Applications**
TEMPO-oxidized cellulose	2.5 – 33.3 wt%	PVDF/ MoS2	Flexoelectric-based devices/Dielectric films/ Nanogenerator/ Energy storage [10, 13, 17, 19, 24]
Cellulose acetate	1-5 wt%	PDA for $BaTiO_3$ coatings, carbonized polymer dots	Ecofriendly cellulose-based dielectric capacitors [7, 8]

Cellulose Type	$BaTiO_3$ Content	Additional Components	Applications
Flexible trilayer cellulosic paper	Not mentioned	Styrene butadiene rubber	Separators in Na-ion batteries [6]
		PVDF	Sepaators in Li-Ion Batteries and Supercapacitors [12]
Carboxymethyl nanocellulose	40-60 wt%	None	Microcapacitors [25]
	0.32 wt%	PEO	Pyroelectric sensors, electromechanical transducers, electrodes [26]
Cellulose nanofibers	15 wt%	PDA for $BaTiO_3$ coatings, P(VDF-TrFE)	Energy storage [5]
	5 wt%	TiO2/PVDF	Pressure sensing [9]
Cyanoethyl cellulose	Not mentioned	GO	Dielectric films in capacitors [18]
	Up to 90 wt%	None/ATO	Dielectric films in capacitors [27, 28]
Regenerated cellulose	2 vol%	None	Dielectric capacitors [23]
		PDA	Dielectric capacitors [20]
3D cellulose scaffold	Not mentioned	P(VDF-TrFE)	Energy harvesting [14]
Cellulose aerogel	46.5, 72.2, 80.5 wt%	PDMS	Flexible piezoelectric nanogenerators [22]
Cotton-sourced cellulose nanofibers	Various wt%	PDA, PVDF-g-MA	Piezoelectric energy harvesting and self-powered sensing [15]
Cellulose nanofibrils	30 wt%	None	Energy storage [21]
Natural cellulose (carrot)	20 wt%	None	Multifunctional sensor [4]
Hydroxypropyl cellulose	2 wt%	None	Energy storage [16]
Bacterial cellulose	Not mentioned	None	Nanogenerators [58]
Wood cellulose fibers	48 wt%	PDDA, PSS	Piezoelectric sensor [59]

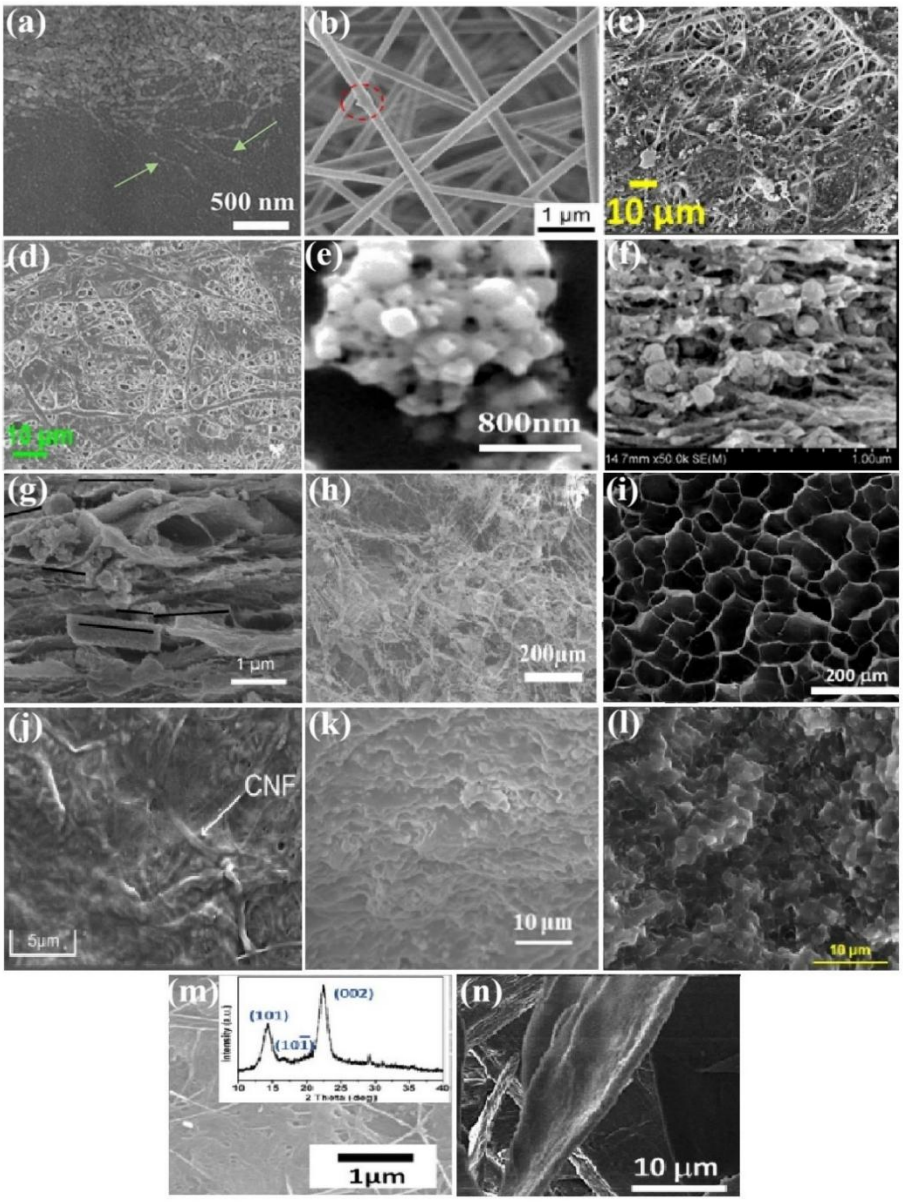


Figure 3: SEM images of TEMPO-oxidized cellulose (a) [10], cellulose acetate (b) [8], trilayer cellulosic paper/$BaTiO_3$ (c) [6], carboxymethyl nanocellulose/$BaTiO_3$ (d) [12], cellulose nanofibers/$BaTiO_3$ (e) [5], cyanoethyl cellulose/$BaTiO_3$ (f) [27], regenerated cellulose/$BaTiO_3$ (g) [23], 3D cellulose scaffold (h) [14], cellulose aerogel (i) [22], cellulose nanofibrils (j) [21], natural cellulose (k) [4], hydroxypropyl cellulose (l) [16], bacterial cellulose (m) [58], Wood cellulose fibers (n) [59].

Mechanical robustness is critical for flexible electronics applications. A universal trade-off between cellulose/$BaTiO_3$ and mechanical properties is evident. The tensile strengths were reported to reach even 335 MPa for the TOCN/MoS_2/$BaTiO_3$ ternary system [17]. Cellulose paper-based separators exhibited tensile strengths of 43.96–50.15 MPa [12], while layered cotton cellulose membranes reached 47.99 ± 4.08 MPa [15]. The study [59] observed a 73% reduction in breaking strength at 48 wt% $BaTiO_3$, while similarly reported decreased tensile strength with increasing $BaTiO_3$ content [24].

In energy harvesting, piezoelectric coefficients (d_{33}) range from 3.8 pC/N cellulose acetate-based hybrid nanogenerators [8] to 191 pC/N for nanocellulose/$BaTiO_3$ composites [25]. The output voltages may reach 48 V in hybridized piezoelectric-triboelectric configurations [22] and power densities up to 42 $\mu W/cm^3$ using 3D cellulose scaffolds, nearly 800% higher than conventional flexible piezoelectric composites [14]. The performance of the cellulose acetate-based hybrid nanogenerators is illustrated in

Figure 4. The TOCN/MoS_2/$BaTiO_3$ ternary system reported by Xu *et al*. achieved d_{33} = 45 pC/N [17], attributed to the synergistic effect of MoS_2 nanosheets creating a "brick-mortar" structure with cellulose nanofibrils. Regarding the operational stability, the authors in [15] demonstrated a duration of over 8400 cycles under an applied force of 5 N at 3 Hz on cotton cellulose interfaced maleic-anhydride-grafted polyvinylidene fluoride (PVDF-g-MA) nanofibers, or even over 15,000 cycles under extreme conditions including underwater and high/low temperature environments for PDA-modified composite with cellulose acetate and $BaTiO_3$ [8].

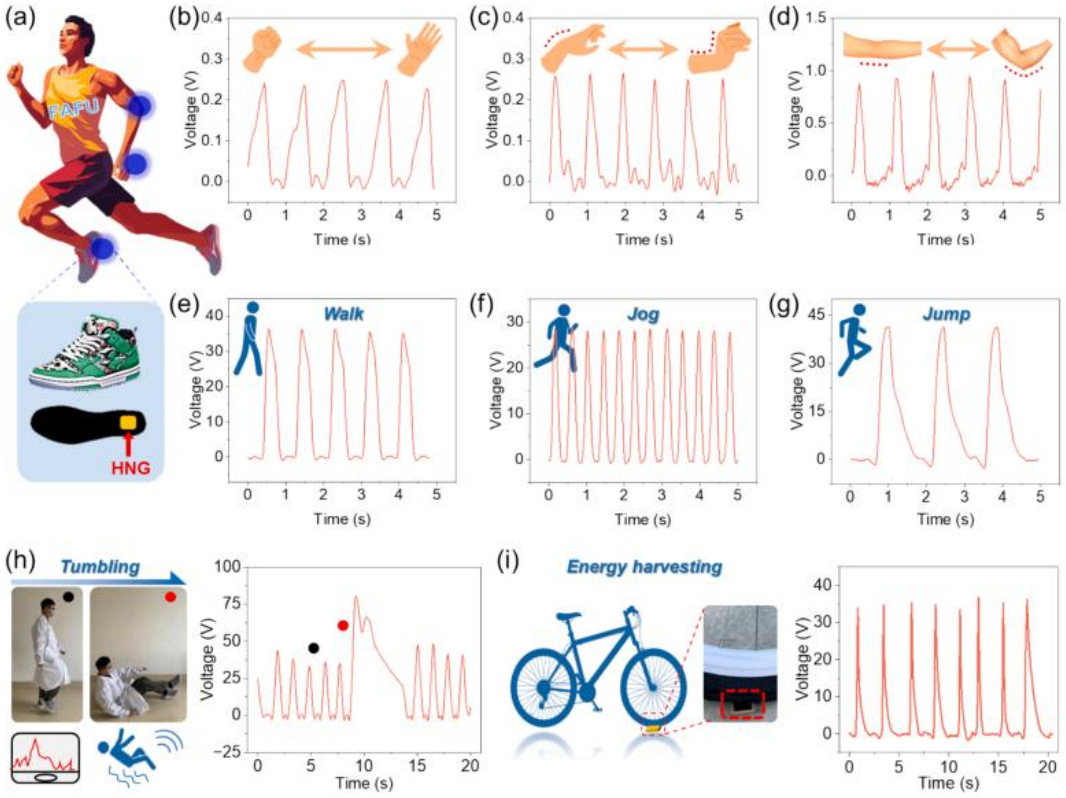


Figure 4: Device performance of cellulose acetate-based hybrid nanogenerators: real-time output voltage curve for (a) human motions. (b) Fist-clenching/relaxing, (c) wrist bending and (d) elbow flexion. (e-g) Real-time output voltage curve when a person walks, jogs and jumps. Output voltage of different motion behaviors: (h) walking with a sudden tumble, and (i) a bicycle passing through the device and its corresponding electrical response [8].

For energy storage, discharged energy densities as high as 17.1 J/cm^3 520 MV/m [20] and dielectric constants up to 188.03 [21] have been achieved, while cellulose-based battery separators deliver electrochemical performance comparable to commercial glass fiber and polyolefin alternatives with superior thermal stability up to 200 °C [6, 12]. The illustration for the performance of the cellulose-based battery separators is given in Figure 5. Performance is governed by several interacting factors: $BaTiO_3$ loading follows a non-linear optimum due to the trade-off between enhanced piezoelectric/dielectric activity and mechanical embrittlement from filler agglomeration [23, 25]; surface modification with polydopamine dramatically improves filler dispersion and breakdown strength [20]; composite architectures such as 3D scaffolds [14], core-shell fillers [9], and sandwich structures [7] enable simultaneous optimization of multiple properties. Additionally, the incorporation of secondary piezoelectric polymers like PVDF substantially boosts output beyond what purely cellulose matrices achieve [14, 15]. It is worth noting that cellulose/$BaTiO_3$ – based systems are consistently valued for their biodegradability, renewability, and low cost [8, 17, 22], with key remaining challenges centering on uniform high-loading dispersion, hygroscopicity management, and closing the breakdown strength gap with commercial dielectric films [7, 20].

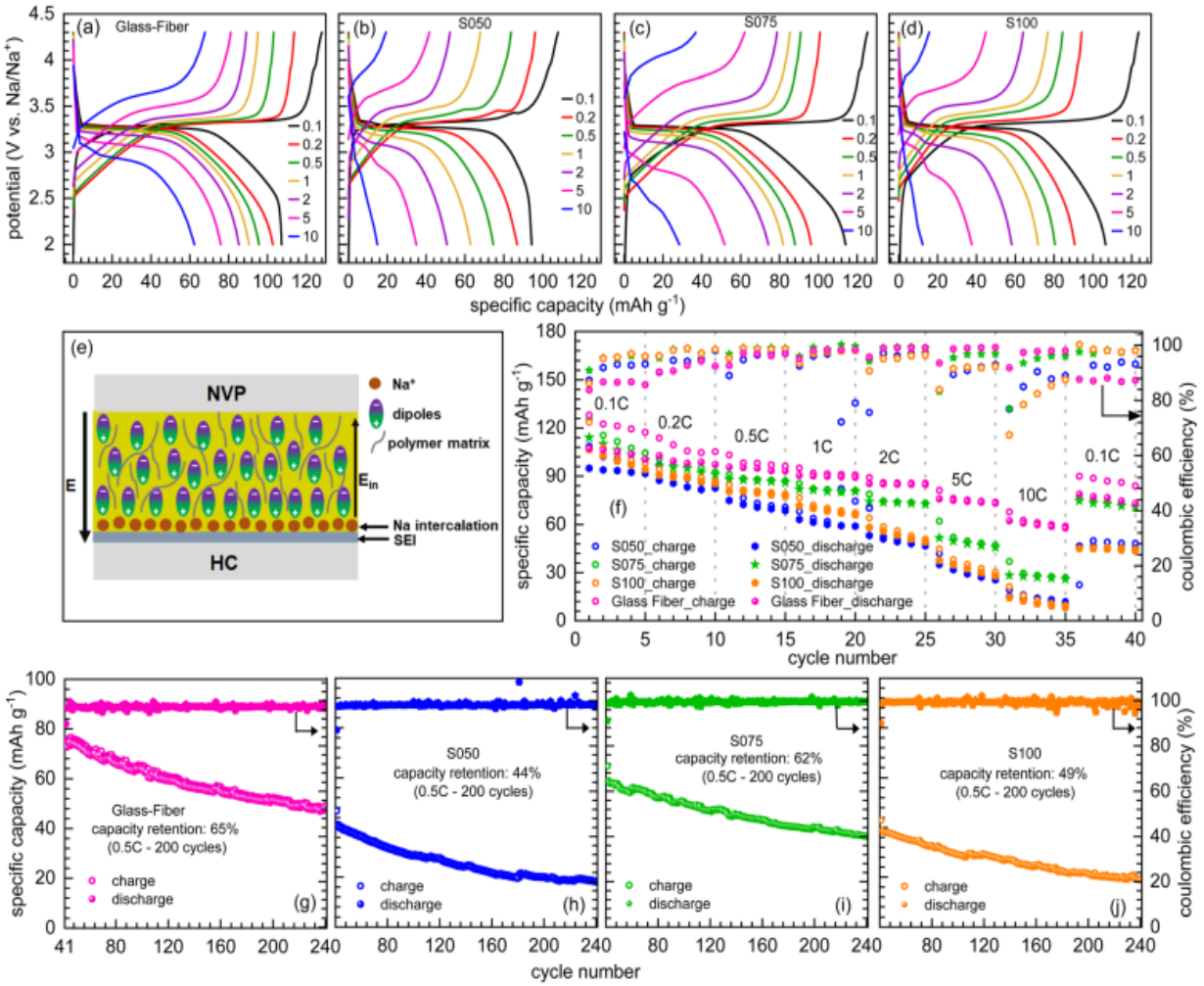


Figure 5: Performance of trilayer cellulosic/$BaTiO_3$ paper separators for Na-ion batteries: (a–d) the galvanostatic charge–discharge profiles; (e) the mechanism for the functioning of separators; (f) the rate performance at the different C rates; (g–j) the cycle life and coulombic efficiency at 0.5C rate between 41 and 240 cycles) [6].

For sensing applications, there are currently relatively few studies on cellulose/$BaTiO_3$-based systems [4, 9, 26, 59]. The most successful material belongs to the work [4], in which 20% $BaTiO_3$ concentration was estimated as optimal for developing flexible, low-cost and recyclable multifunctional sensors in terms of pressure, temperature and humidity sensing response. In previous studies [59], a hybrid piezoelectric paper with loading of 48 wt% $BaTiO_3$ into a stable matrix with wood cellulose demonstrated high piezoelectric coefficient d_{33} = 4.8 ± 0.4 pC/N, promising as a low-cost substrate for developing sensing devices. Another system of cellulose nanofibers/$BaTiO_3$@TiO_2 piezoelectric is also promising for pressure sensors with a piezoelectric coefficient of 84.29 pm/V, a maximum open-circuit voltage of 13.1 V and a short-circuit current of 464.3 nA [9].

3 CELLULOSE/FERROELECTRIC POLYMER – BASED MATERIALS

Cellulose-based materials integrated with ferroelectric polymers have also made a significant impact over the past decade, demonstrating remarkable progress in state-of-the-art applications (Table 2). Notably, energy-related devices dominate the list with several composites designed for energy harvesting and energy storage, while others serve as electrolytes or separators in lithium-ion batteries [5, 13, 14, 19, 29, 30, 35, 37, 39, 41]. Sensing and monitoring is another prominent category, with materials developed for flexible fabric piezoelectric sensors [33], triboelectric textile sensors [40], and human motion monitoring devices [30]. Beyond these, it includes composites tailored for more specialized uses such as self-sustaining antibacterial coating surfaces with electric and magnetic field tunability [31], flexible electrothermal films

[36], water purification membranes [38], touch screens [60], and potential biofriendly optoelectronic devices [42]. In those materials, ferroelectric polymers were combined with various forms of cellulose - including Whatman paper-originated cellulose [29], microcrystalline cellulose [31], regenerated cellulose [37], cellulose acetate [36, 39], cellulose nanocrystals (CNC) [32, 33, 40], silylated cellulose [38], CdS-impregnated cellulose nanocrystals [42], bacterial cellulose [60], cellulose nanofibers (CNF) [30, 34], commercial cellulose paper [41], and TEMPO-oxidized cellulose nanofibrils [13, 19] and 3D cellulose scaffold [14]. Obviously, although the number of studies to date is lower than that of cellulose/$BaTiO_3$-based systems as analyzed above, the types of cellulose employed are considerably more diverse. Some composites also incorporate inorganic fillers such as $LiFe_5O_8$, MoS_2, and CdS to enhance their functional properties [31, 32, 42].

Table 2: Cellulose/ferroelectric polymer-based materials and their applications

Cellulose/ferroelectric polymer-based materials	Applications
Whatman paper-originated Cellulose/PVDF	Electrolytes in Li-batteries [29]
Microcrystalline cellulose/PVDF-HFP/ /$LiFe_5O_8$	Self-sustaining electric and magnetic field-tuned antibacterial coating surfaces [31]
Regenerated cellulose/PVDF	Dielectric capacitors [37]
Regenerated Cellulose/PVDF-HFP	Separators for Li-batteries [35]
Cellulose acetate/PVDF	Piezoelectric nanogenerators [39]
	Flexible electrothermal film [36]
Cellulose nanocrystals/PVDF	Flexible fabric piezoelectric sensor [33]
	Triboelectric textile sensors [40]
Cellulose nanocrystals/PVDF/MoS_2	High-performance piezoelectric textile [32]
Silylated cellulose/PVDF	Water purification [38]
CdS-impregnated cellulose nanocrystals/PVDF	Possible biofriendly optoelectronic devices [42]
Bacterial cellulose/PVDF	Touch screens [60]
Cellulose nanofiber/PVDF	Energy harvesting, environmental monitoring [34]
	Human motion monitoring, mechanical energy harvesting [30]
Commercial cellulose paper/PVDF	Separators for Li-batteries [41]
TEMPO-oxidized cellulose nanofibrils/PVDF/$BaTiO_3$	Energy harvesting, energy storage [13, 19]
Cellulose nanofibers/ P(VDF-TrFE)/ $BaTiO_3$	Energy storage [5]
3D cellulose scaffold/PVDF/ $BaTiO_3$	Energy harvesting [14]

Among ferroelectric polymers, poly(vinylidene fluoride) (PVDF) is the most widely employed material in this class of composites to combine with cellulose. Originally, PVDF is a semi-crystalline thermoplastic polymer known for its excellent chemical resistance, thermal stability, and mechanical strength, remarkable piezoelectric and pyroelectric properties. Let us analyze some cases. In [31], the PVDF-HFP/cellulose/$LiFe_5O_8$ (LFO) nanoparticle nanocomposite exhibits a magnetoelectric effect, enabling multifunctional applications in sensors, actuators, energy harvesters, data storage, and biomedical devices (Figure 6a). As a ternary nanofiber system, it shows strong potential for self-powered antibacterial coatings and electrically or magnetically tunable surfaces for advanced biomedical technologies. In this

architecture, PVDF-HFP contributes ferroelectricity and flexibility for implantable and smart textile applications, LFO nanoparticles provide magnetic responsiveness for sensing and energy harvesting, while cellulose enhances biocompatibility and supports applications such as biomedical platforms and water-oil separation systems. In another study [29], cellulose/PVDF blend films have been developed as solid polymer electrolytes for lithium-ion batteries (LIBs) (Figure 6b), offering a safer alternative to conventional liquid electrolytes by mitigating dendrite formation and preventing organic solvent leakage. The intrinsic phase separation within the blends generates additional free volume, thereby enhancing ionic conductivity and improving overall battery performance. In the opposite, the combination of PVDF and cellulose might improve the breakdown strength for energy density for dielectric capacitors [37] (Figure 6c). Here, by incorporating PVDF to reduce water affinity, regenerated cellulose/PVDF composite films achieved an enhanced energy storage density of 8.3 J/cm^3 at 410 MV/m (at 3 wt% PVDF), significantly outperforming pristine regenerated cellulose and PVDF, thereby broadening the applicability of cellulose-based dielectrics in humid environments. Interestingly, cellulose/PVDF – based compounds could be used to make freestanding flexible films. For instance, freestanding flexible composite films based on CdS-impregnated cellulose nanocrystals (CNCs)/PVDF demonstrate strong potential for advanced device applications owing to the renewable, biodegradable, and non-toxic nature of CNCs combined with the ferroelectric functionality of PVDF [42]. The incorporation of CNCs enhances mechanical performance and flexibility, enabling applications in biomimetic robotics, actuation systems, and energy-harvesting devices, similar to other PVDF-based composite platforms (e.g., PVDF/ZnO systems). Moreover, the pronounced photoluminescence characteristics introduced by CdS nanoparticles expand their applicability toward biofriendly optoelectronic devices.

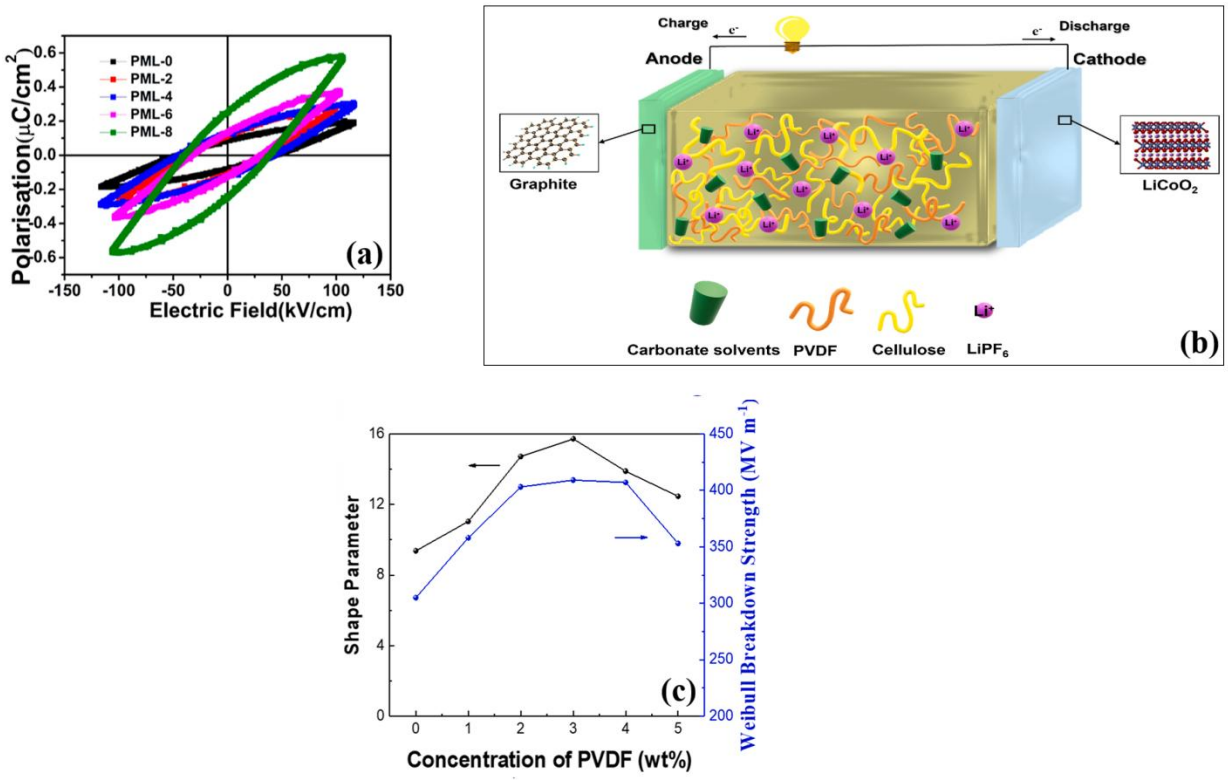


Figure 6: P-E hysteresis loop of PVDF-HFP/cellulose/$LiFe_5O_8$ [31] (a), distribution of cellulose, PVDF and solvent in the cellulose/PVDF based electrolyte for Li-ion batteries [29] (b), and effect of PVDF solution concentration on Weibull breakdown strength and shape parameter of regenerated cellulose/PVDF composite films for dielectric capacitors [37].

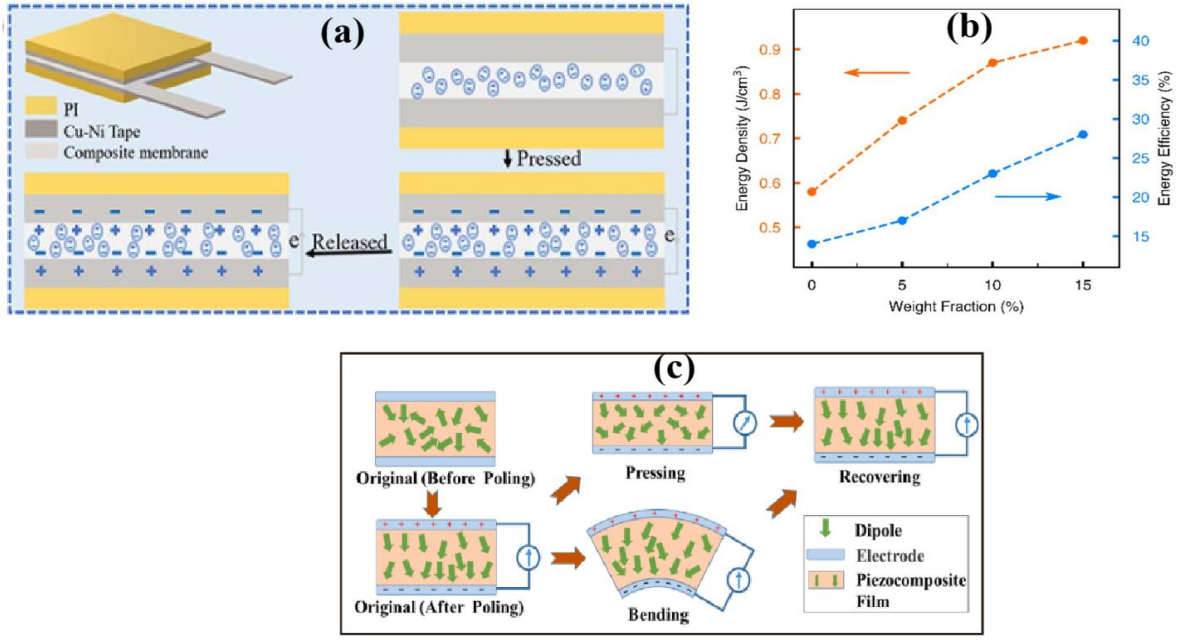


Figure 7: Operating scheme for TEMPO-oxidized/PVDF based piezoelectric generator [13] (a), energy density and energy efficiency of P(VDF-TrFE) thin films at different compositions [5] (b), and schematic diagram of the working mechanism of energy harvesting devices based on (P(VDF-TrFE)-impregnated $BaTiO_3$ nanoparticles within 3D cellulose scaffold [14] (c).

More advanced, to combine the advantages of cellulose and various ferroelectric components, few studies have developed flexible materials by integrating cellulose, $BaTiO_3$, and ferroelectric polymers into a single system [5, 13, 14, 19]. In [13] (Figure 7a), PVDF and TEMPO-oxidized CNFs were used to fabricate a compact CNF/PVDF/$BaTiO_3$ composite membrane with good mechanical properties (tensile strength 18.61 ± 3.75 MPa; elongation at break 3.06 ± 1.33%). A thin piezoelectric generator assembled from this membrane delivered 4.4 V and 200 nA, powered an LED, charged a 1 mF capacitor to 3.66 V in 500 s, and showed a d_{33} of 5.25 ± 1.04 pC/N. The designed devices also exhibited high sensitivity to human motion, demonstrating strong potential for sensing and energy harvesting applications [13] and excellent energy storage properties [19]. A next study offered high-energy-density P(VDF-TrFE) nanocomposite films reinforced with cellulose nanofibers and dopamine-functionalized $BaTiO_3$ nanoparticles [5] (Figure 7b). Here, a nanoparticle mixture comprising carboxyl cellulose nanofibers and polydopamine-coated $BaTiO_3$, introduced into a P(VDF-TrFE) ferroelectric polymer matrix. The nanofiller content as high as 15 wt% was successfully incorporated, followed by a thorough evaluation of the ferroelectric and energy-storage properties. Although thinner films are more susceptible to surface and bulk defects that may adversely affect device performance compared with thicker counterparts, the adopted fabrication approach allowed operation at relatively low voltages (~150 V_{pp}), lower than those commonly reported in the literature. In another case with employing (P(VDF-TrFE)-impregnated $BaTiO_3$ nanoparticles within 3D cellulose scaffold [14] (Figure 7c), the obtained results showed a power density of 42 $\mu W/cm^3$, representing an almost eightfold enhancement compared to previously reported conventional flexible piezoelectric composites. Owing to its straightforward fabrication process and scalability, the synthesis approach suggested in this study provides a promising pathway toward next-generation flexible, high-efficiency energy harvesting systems.

4 MATERIALS BASED ON CELLULOSE COMBINED WITH OTHER FERROELECTRICS

In addition to $BaTiO_3$ and ferroelectric polymers, which have been extensively studied as discussed above, cellulose has also been combined with various other ferroelectrics such as lead zirconate titanate (PZT) [47-52], strontium titanate ($SrTiO_3$) [45, 46], imidazolium perchlorate ($ImClO_4$) [43, 44], triglycine sulfate (TGS) [54, 55], Rochelle salt (RS), sodium nitrite ($NaNO_2$) [56] and tris-sarcosine calcium chloride (TSCC)

[57]. Although the number of studies on this kind of materials remains limited, they demonstrate significant potential for applications in flexible electronics, as well as promising opportunities for further research expansion in the future. The remarkable materials with their practical applications are listed in Table 3 below.

Table 3: Materials based on cellulose combined with other kinds of ferroelectrics and their applications

Material System	Applications
PZT/microfibrillated cellulose (MFC) hybrid films	Wearable plantar pressure sensors for healthcare monitoring, and sports injury detection [48]
PZT-nanocellulose (NC) films	Sensors, actuators, energy harvesters, structural health monitoring [50]
PZT-ethyl cellulose on Ni-coated Cu foil substrates	Flexible piezoelectric electro-generators for energy harvesting [52]
PZT/cellulose nanocrystal (CNC)/ polyurethane	Wearable electronic devices [51]
PZT/microfibrillated cellulose (MFC)/PVA	Wearable piezoelectric nanogenerator [47]
PZT/banana-source cellulose/MWCNT	Flexible sensors [49]
$SrTiO_3$ nanoparticle/Cellulose ether /citric acid	Solar cells and electrostatic capacitors [46]
$SrTiO_3$ powder/cellulose-assisted liquid-phase precursor method	Multi-layer ceramic capacitors (MLCCs) and dielectric devices [45]
$ImClO_4$/bacterial cellulose	Biodegradable flexible mechanical sensors [43, 44]
RS/a laser-drilled wood template	Piezoelectric Power Generators [53]
TGS/cellulose nanoparticles/MWCNT	Not yet [54]
TGS/cellulose nanofibers	Not yet [55]
$NaNO_2$/cellulose nanofibers	Not yet [56]
TSCC/cellulose nanoparticles	Not yet [57]

The most prominent is wearable and biomedical sensing, where PZT-cellulose films enable plantar pressure monitoring for the rehabilitation of diabetic patients and the detection of sports injury [48] (Figure 8a). Energy harvesting and power generation constitute the second major domain, with applications ranging from harvesting waste mechanical energy from walking for wireless sensor systems to flexible piezoelectric nanogenerators [47, 50, 52] (Figure 8b). In the PZT-based systems, cellulose serves primarily as a flexible, biocompatible matrix enabling conformal contact with the human body or mechanical structures. This explains the convergence of five PZT-cellulose studies toward wearable sensing, energy harvesting, and environmental monitoring. The specific application selected depends largely on the composite architecture: film arrays configured for spatial pressure mapping target biomedical sensing [48], whereas fiber composites optimized for high voltage output under impact loading target power generation.

Cellulose-based ferroelectric composites demonstrate diverse application potentials with $SrTiO_3$, RS and $ImClO_4$ (Table 3). $SrTiO_3$ nanoparticle/cellulose ether/citric acid composites were found to be suitable for applications in solar cells and electrostatic capacitors due to their high dielectric properties and processability [46]. Similarly, $SrTiO_3$ powder/cellulose composites are used in multi-layer ceramic capacitors (MLCCs) and other dielectric devices, highlighting their potential in energy storage and electronic components [45]. Meanwhile, a single work on $ImClO_4$/bacterial cellulose hydrogel composites is devoted to designing biodegradable flexible mechanical sensors, making them promise for sustainable and flexible electronic applications for that the bacterial cellulose hydrogel sensor is fully degradable into

glucose and oligosaccharides, with the molecular ferroelectric recyclable for reuse [43] (Figure 8c). In general, cellulose functions either as a matrix providing film-forming capability or as a synthesis aid enabling nanoparticle size control, rather than as a structural element in the final device. This sustainability dimension is echoed by researchers, who emphasize eco-friendly nature of materials. These studies suggest that environmental end-of-life considerations are increasingly shaping application selection, particularly for disposable or temporary sensing scenarios. To enhance stress transfer and mechanical stability of the active piezoelectricity, wood can be designed in the form of templates with laser-drilled hole arrays (700 μm diameter) were fabricated [53] (Figure 8d). With combining it with RS [53], a fully renewable device based on Rochelle salt integrated into a laser-drilled wood template forms ordered crystal pillar arrays via melt crystallization, achieving up to 30 V and 4 μA with a 45° shearing configuration - about 10 times higher power than single-crystal Rochelle salt. The device uses direct laser graphitization to create low-resistance electrodes (36 Ω sq^{-1}), is fully recyclable, and delivers performance comparable to lead-based devices while maintaining a significantly lower environmental footprint.

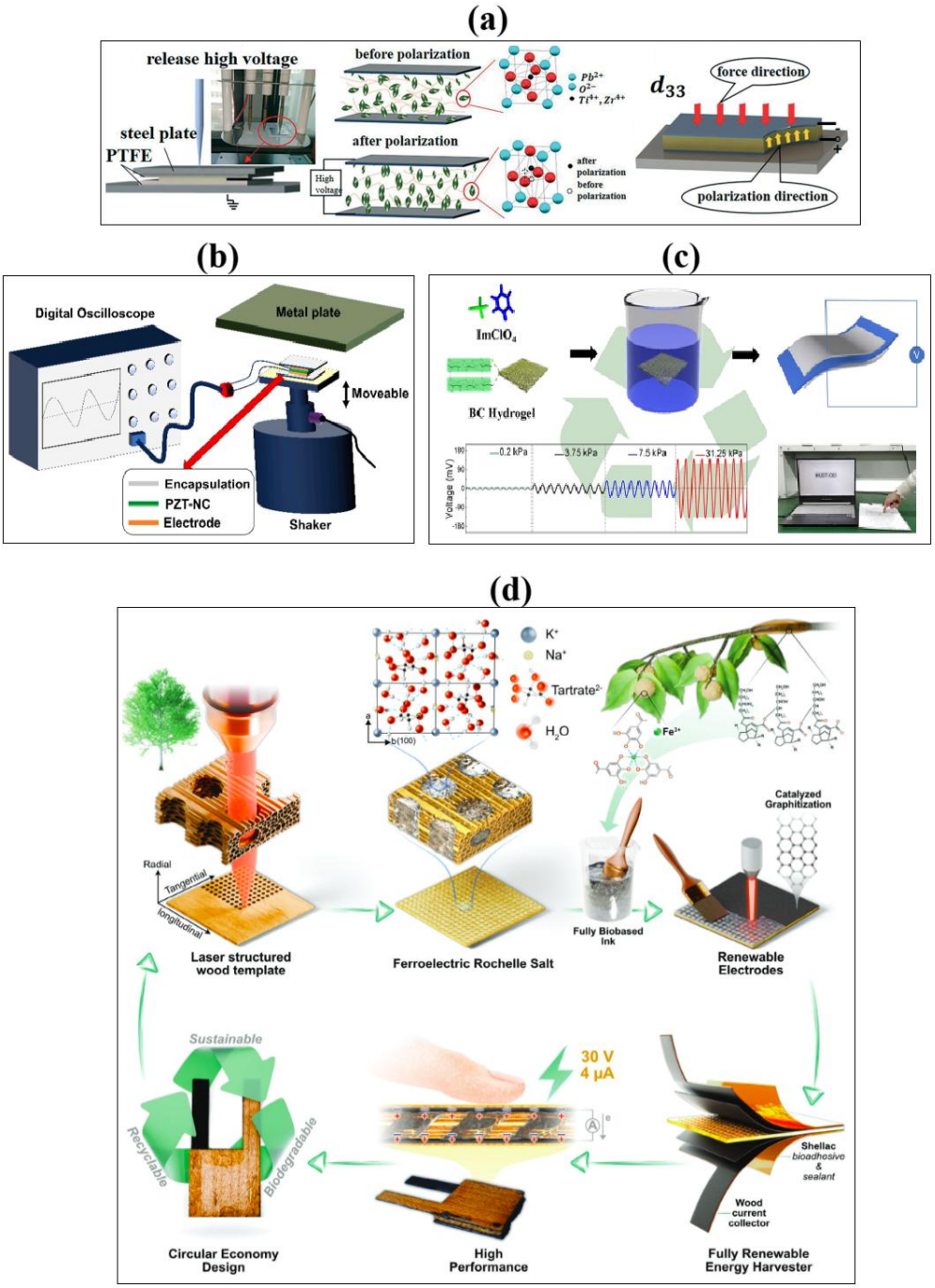


Figure 8: Sensitive response of PZT/microfibrillated cellulose hybrid films to pressure (a) [60-2024], piezoelectric performance of PZT/nanocellulose films (b) [50], (c) $ImClO_4$/ Bacterial cellulose hydrogen – based biodegradable and recyclable piezoelectric sensor [43], and schematic illustration of the preparation and energy harvesting performance for Rochelle salt- in-Wood piezoelectric power generators (d) [53]

Other cellulose-based materials with TGS [54, 55], $NaNO_2$ [56] and TSCC [57] have not yet been implemented in practical device fabrication. Their mechanical properties have not been assessed completely. In this regard, they can only be considered as potential for next development, which would be made by adding components with high elasticity. Up to now, their ferroelectricity has been promising. For instance, the work [54] developed a new nanocomposite composed of TGS (79 wt%), multiwalled carbon nanotubes (1 wt%), and cellulose nanoparticles (20 wt%), which were tested under compressive pressures ranging from 5 to 200 MPa. The results indicated that increasing pressure enhances both permittivity and

electrical conductivity due to the formation of more effective conductive networks by the carbon nanotubes. The most favorable performance was observed within the pressure range of approximately 50–150 MPa, whereas pressures outside this interval caused instability, such as time-dependent permittivity decay and alterations in polarization switching and conductivity. In another case [57], the combination of TSCC and cellulose nanoparticles demonstrated the shift of phase transition point under various pressures from 0.1 to 0.7 GPa. For nanocellulose fibers, as reported in [55], a system containing TGS embedded into cellulose nanochannels showed considerably high dielectric permittivity at low frequency (10^{-3}-10^{6} Hz), high sensitivity to frequency and the expansion of ferroelectric phase. Similarly, the sensitivity of dielectric permittivity to frequency was also detected for $NaNO_2$ confined in cellulose nanochannels [56]. However, the phase transition was found to decrease. For those materials, their properties are controlled by the interaction between cellulose and ferroelectric components at low temperatures, below room temperatures as usual [54, 55, 57]. At higher temperatures, the size effects take place [56].

5 CONCLUSIONS

A review of the up-to-date literature data indicated that the composites containing cellulose/$BaTiO_3$ constitute the most extensively studied system among cellulose-based ferroelectric materials. This is followed by cellulose/PVDF – based compounds, while comparatively fewer studies have focused on cellulose/PZT, cellulose/$ImClO_4$, and other related material materials. These materials have been widely applied in flexible electronic devices, such as pressure and strain sensors, piezoelectric nanogenerators, wearable energy harvesters, flexible capacitors, dielectric layers, and self-powered sensing platforms, and so on. In most of the materials analyzed, cellulose does not act as an elastic component but rather as an important constituent that enhances the stability of electrical parameters under repeated mechanical deformation over multiple cycles.

The above analysis also revealed several research gaps, as well as promising research directions that may be pursued in the next stage of development:

- First, for cellulose/$BaTiO_3$-based composites, long-term mechanical stability under continuous operation remains a critical issue that requires further improvement. To date, blending with PVDF - a polymer known for its superior mechanical durability - has been considered an effective strategy (Table 1). However, PVDF itself is a ferroelectric material, which introduces additional complexity in controlling and tailoring the overall ferroelectric response of the composite system. To address this limitation, silicone rubber may represent a more suitable alternative matrix. Silicone rubber not only exhibits excellent mechanical flexibility and long-term durability but also functions as a purely dielectric material, thereby avoiding interference with the intrinsic ferroelectric behavior of $BaTiO_3$. More importantly, silicone rubber possesses favorable elastic compliance, enabling efficient mechanical stress transfer to the embedded ferroelectric particles. For enhanced stability and interfacial compatibility, the ferroelectric particles should be surface-encapsulated or coated to ensure protection and improved stress coupling within the composite structure.
- Second, regarding cellulose/$ImClO_4$-based materials, although the reported results are highly promising for biodegradable flexible mechanical sensors, the number of available studies remains very limited, with only a few publications reported to date. This is clearly not commensurate with its intrinsic potential, indicating a significant research gap that warrants further systematic investigation. Given the intrinsic biodegradability of cellulose and the functional properties introduced by $ImClO_4$, this class of materials holds considerable promise for next-generation electronics. Specifically, their applications may include flexible biomedical devices, disposable health-monitoring sensors, transient electronic systems, and other environmentally friendly electronic platforms where mechanical compliance, biodegradability, and functional responsiveness are simultaneously required.
- Third, cellulose-based composites incorporating other ferroelectric materials (Rochelle salt, triglycine sulfate, sodium nitrite, etc.) also exhibited a substantial research gap. Specifically, while mechanical stimuli (e.g., compressive pressure) have been reported to induce variations in key electrophysical parameters such as dielectric constant, phase transition temperature, and polarization, these studies generally did not demonstrate cyclic repeatability of the observed

responses. Such a limitation critically undermines their practical relevance for applications in force sensors, pressure sensors, and related electromechanical devices, where stable and repeatable performance over multiple operating cycles is essential. In most reported works, there has been no clear evidence indicating whether these electrical parameters can recover to their initial states upon release of the applied compressive stress. From our point of view, this issue may be intrinsically related to the limited elastic recovery of cellulose. Cellulose does not exhibit pronounced elastic behavior, or its recovery kinetics may be relatively slow, which could prevent full restoration of the electrical properties after mechanical unloading. Therefore, incorporating an elastomeric component such as PVDF or silicone rubber into these systems may provide a viable strategy to enhance mechanical resilience and improve the operational cycling stability of the materials.

Among those research gaps, cellulose/$ImClO_4$-based materials appear to be the most promising, as the development of cellulose/$BaTiO_3$ and PVDF-based composites has reached a relatively mature stage. Meanwhile, materials based on Rochelle salt, triglycine sulfate, and sodium nitrite have not yet demonstrated sufficiently favorable properties for flexible electronics. In contrast, although only a limited number of cellulose/$ImClO_4$-based materials have been developed, they have already demonstrated promising performance in practical applications.

Overall, it can be observed that cellulose/ferroelectric-based materials possess significant development potential and promising prospects for future applications. Although the number of publications over the past decade has been relatively limited, the already-implemented-applications have clearly demonstrated their position in the field of flexible electronics, particularly in healthcare technologies and soft robotics. This overview is of significant importance for the development of core technologies in the field of smart electronics.

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VẬT LIỆU TIÊN TIẾN TRÊN CƠ SỞ XENLULO/VẬT LIỆU SẮT ĐIỆN ỨNG DỤNG TRONG ĐIỆN TỬ LINH HOẠT: BÀI TỔNG QUAN NGẮN

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Tóm tắt. Điện tử linh hoạt đang ngày càng trở nên thiết yếu đối với công nghệ hiện đại nhờ những đặc tính cơ điện độc đáo, bao gồm khả năng uốn dẻo, khả năng kéo giãn và khả năng ôm sát bề mặt, cho phép các linh kiện điện tử tiếp xúc mật thiết với những bề mặt cong, biến dạng động và tương thích sinh học. Xu hướng này đã thúc đẩy sự phát triển nhanh chóng của các vật liệu mới với những yêu cầu ngày càng khắt khe về tính năng và hiệu suất hoạt động. Mặc dù xenlulo và vật liệu sắt điện đã khẳng định được vai trò riêng biệt trong các công nghệ điện tử, việc tích hợp hai thành phần này trong cùng một hệ vật liệu chỉ mới thu hút sự quan tâm nghiên cứu đáng kể trong những năm gần đây, với thời gian phát triển chưa đầy một thập kỷ. Tuy đây là một nhóm vật liệu tương đối chuyên biệt với số lượng công bố khoa học còn hạn chế, phạm vi ứng dụng của chúng lại rất rộng trong nhiều lĩnh vực công nghệ hiện đại, đặc biệt là chăm sóc sức khỏe và robot mềm. Vì vậy, bài tổng quan này nhằm cung cấp cho các nhà nghiên cứu cái nhìn toàn diện về các vật liệu trên cơ sở xenlulo/vật liệu sắt điện trong khoảng một thập kỷ gần đây, tập trung tổng hợp và phân tích các tính chất, ứng dụng, phương pháp chế tạo, ưu điểm và hạn chế của chúng, đồng thời đề xuất những định hướng nghiên cứu tiềm năng trong tương lai. Nội dung tổng quan này có ý nghĩa quan trọng đối với việc phát triển các công nghệ lõi trong lĩnh vực điện tử thông minh.

Từ khóa. Xenlulo, vật liệu sắt điện, vật liệu trên cơ sở xenlulo/vật liệu sắt điện, điện tử linh hoạt.

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