

Perspective

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From natural leather to intelligent wearable nanocomposite: design and application

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How to cite this article: Fan Z, Sang M, Gong X, Leung KCF, Xuan S. From natural leather to intelligent wearable nanocomposite: design and application. *Soft Sci* 2024;4:11. <https://dx.doi.org/10.20517/ss.2023.47>

Received: 22 Oct 2023 **First Decision:** 21 Nov 2023 **Revised:** 4 Dec 2023 **Accepted:** 27 Dec 2023 **Published:** 20 Feb 2024

Academic Editors: Zhifeng Ren, Ramses V. Martinez **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang

Abstract

As a natural material, leather has been widely used in daily life due to its high biocompatibility, wearing comfort, and excellent mechanical strength. However, with the increasing demand for a better life among people, the single function of leather has difficulty in meeting the requirements, which limits its application prospects. It is particularly important to develop multifunctional leather composites with diverse characteristics. Therefore, leather can be modified and functionally designed through physical and chemical methods towards intelligent wearable devices. From this perspective, we review the research progress of intelligent leather-based wearable composites, mainly focusing on the preparation methods and application directions in recent years. Finally, we emphasize the challenges that leather composites will face in practical applications and propose future research directions.

Keywords: Leather, flexible electronics, soft sensors, safeguarding, thermal management

INTRODUCTION

Leather, as an ancient natural polymer, has a simple source and preparation, abundant reserves, high



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biocompatibility, good breathability, strong stability, wear resistance, biodegradability, *etc.*^[1-3]. The preparation process for the leather preserves the flexibility and strength of animal skin; thus, it has been used as a popular clothing and armor material throughout history^[4,5]. In the early days, people's demand for leather products was practical, beautiful, sturdy, and stab-resistant. Compared to traditional weaving fabrics, the natural 3D weaving structure and intertwined fiber bundles of leather can better reduce acupuncture damage. However, with the rapid development of soft functional composites and flexible electronic devices, the single function and application of leather composites cannot satisfy the requirement^[6,7]. In comparison to flexible substrates with a single structure, such as polydimethylsiloxane (PDMS), polyethylene terephthalate (PET), *etc.*, the leather is more easily modified and highly breathable due to the natural porous structures^[8]. Furthermore, the mechanical strength of leather is reliable compared to other fiber-based substrates, such as cotton-based textiles and polyimide (PI)^[9]. Therefore, leather will be expected to have more potential applications in wearable electronic devices, electromagnetic interference shielding, flame retardant protection, and intelligent thermal management^[10].

When processed into leather, the original skin of animals requires many steps, such as removing impurities, tanning, fat-liquoring, and drying^[11,12]. After a series of treatments, the nanoscale collagen fibers, unique 3D porous network structure, and multilevel hierarchical structure were ultimately retained^[13]. Based on this special microstructure and biocompatible collagen fibers, a large amount of research has emerged on multifunctional leather composites in recent years^[14]. On the one hand, various functional materials were selected to combine with collagen fibers to form physical adhesion or chemical crosslinking bonds^[3,15], which were composed of conductive materials including graphene oxides (GO)^[16,17], carbon nanotubes (CNTs)^[18,19], silver nanowires (AgNWs)^[20], MXene^[21], poly(3,4-ethylenedioxythiophene)-poly(styrene sulfonate) (PEDOT:PSS)^[22], *etc.*, and insulating materials include silicon dioxide particles^[23], boron nitride^[24], montmorillonite^[25], *etc.* Then, the structural design was carried out on the leather at the macro- or micro-scale by utilizing the above functional materials to obtain leather composites with editable properties^[26]. These methods are similar to dyeing in the leather-making process. On the other hand, the natural microstructure of leather fiber networks could be used for *in-situ* growing hydrogels or other composites through the induction of catalytic materials. At last, the obtained hydrogels or other composites could be further designed by the above functional materials, which enabled leather composites to get other functions^[27,28].

By combining various functional materials, the smart leather with tunable functionalities, such as conductive leather^[29,30], electromagnetic shielding leather^[31], flame retardant leather^[32,33], antibacterial leather^[34-36], thermal camouflage leather^[37], waterproof leather^[11,38], and so on, has been developed. From this perspective, we mainly introduce several common and efficient preparation methods for constructing intelligent leather composites and then focus on their applications in flexible sensors, electromagnetic interference shielding, flame retardant, body safeguarding, thermoregulatory clothing, and other aspects. Finally, the potential difficulties and future development trends of leather composites in practical applications are discussed. This discussion will help intelligent leather composites enter people's daily lives and promote the industrialization development stage of functional leather^[39].

DESIGN AND PREPARATION OF LEATHER COMPOSITES

Currently, there have been many studies on the preparation of leather composites. In this section, five common and effective methods are introduced in detail, including vacuum-assisted filtration, spraying, laser direct writing (LDW), *in-situ* growth, and multilayer assembly.

Vacuum-assisted filtration

The method of vacuum-assisted filtration utilizes a vacuum environment to provide a pressure difference between the upper and lower sides of leather, which drives functional materials to enter the interior of the leather and combine with collagen fibers. Then, the samples were dried to obtain leather composites. Due to its unique layered structure, there are significant differences between the two sides of leather. The grain side is composed of collagen fibers and elastic fibers, and the fiber bundles are finer and more tightly woven, presenting an uneven shape^[40]. The fiber side is composed of interwoven bundles of collagen fibers of different thicknesses, forming a three-dimensional network, and its tightness is positively correlated with the mechanical properties of leather. Ma *et al.* utilized this characteristic to put the fiber side of the leather upwards, and AgNWs were dissolved and infiltrated into the porous structure of the leather through vacuum-assisted filtration [Figure 1A]^[41]. Strong interactions between AgNWs and collagen fiber bundles could be generated through hydrogen bonding, forming an efficient three-dimensional conductive network in leather. The pores of leather range from tens to hundreds of nanometers, so nanoscale functional materials, such as MXene, CNTs, GO, poly(3,4-ethylenedioxythiophene) nanofibers (PEDOT NFs), and ionic liquids, within this scale can be used to prepare leather composites by vacuum-assisted filtration^[42].

Spraying and soaking

The methods of spraying and soaking are attaching functional materials to leather through physical processes, relying solely on the binding ability of functional materials and leather collagen fibers, which is relatively simple and convenient in terms of process. In general, some polymer solutions, non-metal, and metal particles are used to spray onto the leather substrate to form functional coatings, which can strengthen the interfacial bonding between the material and leather due to soaking during the spraying process^[24,43]. Wilson *et al.* used bimetallic copper-iron oxide nanoparticles to spray on the surface of the leather as an electromagnetic coating^[15]. The formed electrically conductive and magnetically active bifunctional leather demonstrated the application possibilities in operating intelligent screens and magnetic switches. Li *et al.* soaked La₂O₃ and Bi₂O₃ nanoparticles in sheep leather and sprayed them on the upper and lower surfaces of leather as coatings, greatly increasing the particle load and enhancing its X-ray protection performance^[44]. Mo *et al.* also combined spraying and vacuum-assisted filtration to filter acidified CNTs on the fiber side and sprayed porous cellulose acetate on the corium side to obtain multifunctional double-layer leather composites, greatly utilizing the layered structure of leather [Figure 1Ba]^[45]. It is obvious that one side of the leather becomes black after filling acidified multiwalled carbon nanotubes (a-MWCNTs), and the other side turns white after spraying porous cellulose acetate. The resulting double-layer leather composites maintain good mechanical performance and breathability [Figure 1Bb-f].

Laser direct writing

In recent years, LDW has gradually become a high-precision and efficient processing technology^[46,47]. Many fabric-based flexible electronics were developed by the LDW technique, and the various carbon precursors were converted into graphene during the laser scanning in the textile. Based on maskless, design flexibility, and pattern editable characteristics of LDW, Yang *et al.* used a femtosecond laser on Kevlar fabric to induce graphene for various electronic textile applications^[48]. It is simple to construct wearable sensors in various textile structures by LDW. Leather, as an emerging biomaterial, contains a large amount of carbon elements. Various flexible electronic devices also can be manufactured without the need for other functional materials by combining computer control with micro-processing technology. Local high temperatures are generated by laser irradiation on the leather substrate to achieve carbonization. Wang *et al.* used the LDW method to induce the carbonization of collagen fiber on the surface of the leather for fabricating wearable sensors. The high control accuracy could directly characterize complex structures, such as arrays, on the surface [Figure 1Ca-d]^[49]. In this case, the collagen fibers transformed from insulation to conductive materials after carbonization and could directly serve as strain sensors to detect tensile and compressive strains. Zhang

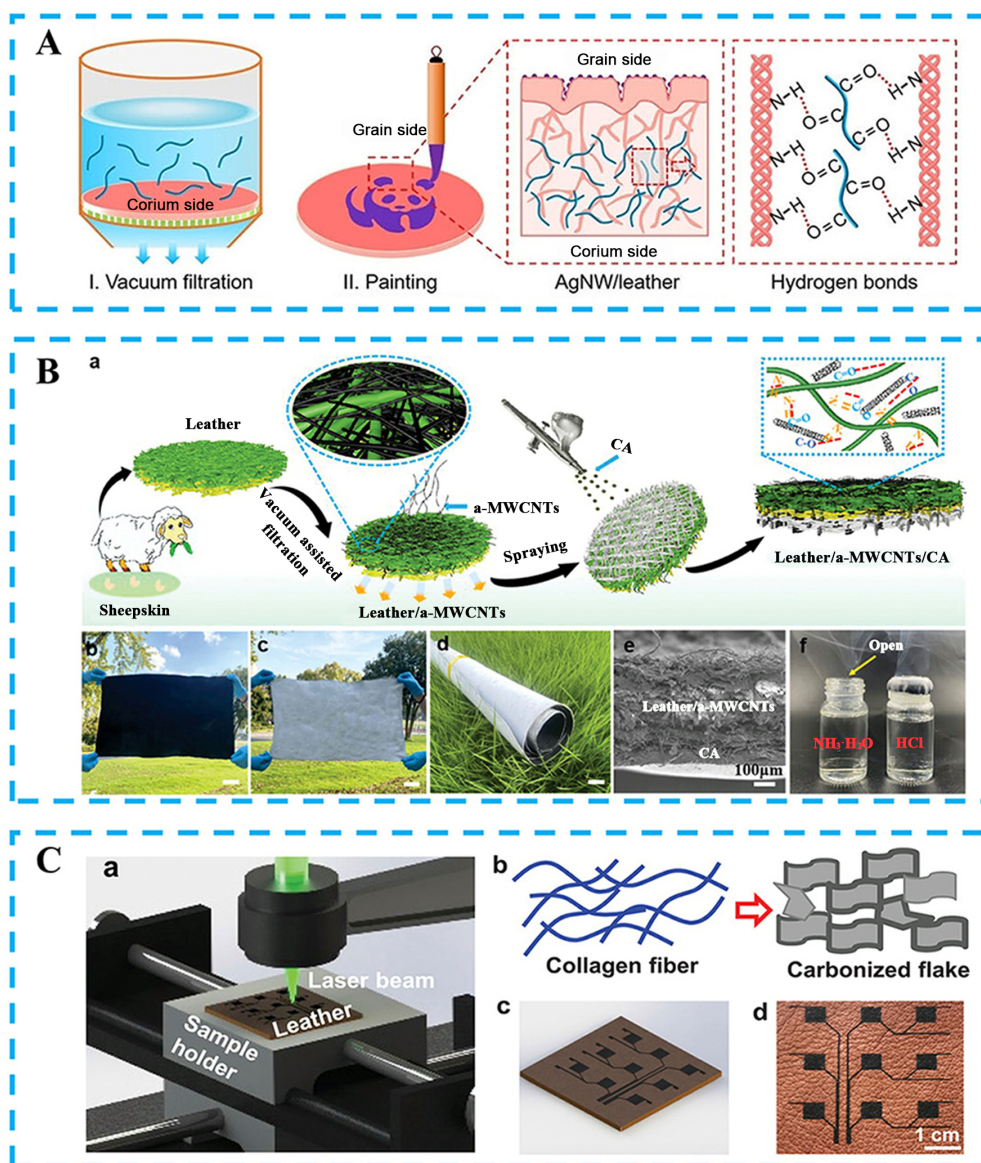


Figure 1. The preparation methods of leather composites. (A) Schematic illustration for fabricating AgNW/leather nanocomposites by vacuum-assisted filtration^[41]. Reprinted with permission. Copyright 2022, Wiley-VCH; (Ba) Schematic diagram of the fabrication of leather/a-MWCNT/CA fabric by spraying and vacuum-assisted filtration; (Bb-f) Photographs of the color, bendability, cross-sectional characterization, and breathability of leather/a-MWCNT/CA fabric^[45]. Reprinted with permission. Copyright 2023, Wiley-VCH; (Ca) A schematic shows the sensor fabrication on the leather by laser direct writing and (Cb) another schematic shows the conversion of collagen fibers in the leather to carbon flakes by the LDW; (Cc and d) Schematic and photograph of a 3×3 sensor array^[49]. Reprinted with permission. Copyright 2020, Wiley-VCH. AgNW: Silver nanowire; a-MWCNT: acidified multiwalled carbon nanotubes; LDW: laser direct writing.

et al. prepared the cross-sensing arrays on the leather substrate with the assistance of LDW technology^[21]. The final product exhibits effective control for mechanical hand movements and human-machine interaction switches, which indicates the high convenience and application potential of the LDW method.

***In-situ* polymerization**

Originally, *in-situ* polymerization was the filling of reactive monomers into the interlayer of nanolayered materials, allowing them to undergo polymerization reactions between the layers. The natural hierarchical 3D network structure of leather provides an interpenetrating fiber network for the *in-situ* growth of

polymers^[50]. By configuring different precursor solutions, they can easily flow in the porous structure of the leather and conduct gelation^[28]. Fan *et al.* used natural goat skin as the substrate and dipped the acrylic monomer, Zr⁴⁺ ions, carbon quantum dots@nanosilver particles (CQDs@AgNPs), and 1,3-propanediol (PDO) into the fiber skeleton of leather. Then, the AA monomer was *in-situ* polymerized to obtain a multifunctional hydrogel containing the leather skeleton [Figure 2Aa]^[27]. The 3D network of leather in ionic gel became an effective flow channel for loading CQDs@AgNPs and PDO, which endowed the hydrogels with excellent mechanical properties, self-adhesiveness, transparency, UV shielding, antibacterial, biocompatibility, and conductivity. Furthermore, the Zr(SO₄)₂ could form a strong interfacial bonding with collagen fibers to enhance the network structure; therefore, the mechanical properties of leather composites were strengthened [Figure 2Ab]. This method provides effective design ideas for the development of intelligent, flexible electronic skins.

Multilayer assembly

Sandwich structures can enhance the overall mechanical properties of composites through the synergistic coordination of different components^[51,52]. Fan *et al.* proposed a flexibility-toughness coupling design strategy to develop intelligent anti-impact leather. By assembling flexible shear stiffening gel (SSG), tough leather, and nonwoven fabric (NWF) into a Leather/SSG/NWF sandwich structure, the mechanical properties of the resulting leather composite were greatly improved [Figure 2B]^[53]. At the same time, the leather layer could also be designed with special functions. For example, the MXene nanosheets could be combined with leather fibers through vacuum-assisted filtration, and then the wearable Leather/MXene/SSG/NWF safeguarding leather composite with excellent sensing, thermal management, and electromagnetic interference shielding was obtained. Obviously, this idea can be further expanded for the multifunctional design and application of intelligent leather [Figure 2C]^[54].

MULTIFUNCTIONAL APPLICATIONS OF LEATHER COMPOSITES

By combining various functional materials with leather, a variety of leather composites, including conductive leather, electromagnetic shielding leather, flame retardant leather, thermal management leather, *etc.*, have been successfully developed^[6,26,55]. Then, intelligent leather composites are further obtained by structural design and assembly based on single-function leather, which can be widely used for flexible sensors, electromagnetic shielding devices, safety protection, flame retardant, intelligent displays, and intelligent thermal management. As shown in Table 1, the preparation methods and functionalities of different leather composites based on various materials are summarized to understand intuitively. Obviously, intelligent leather composites provide an important research direction for the development of wearable electronic devices.

Flexible sensors

Flexible sensors have broad application prospects in human motion monitoring, human-machine interactions, and the intelligent wearable field^[56,57]. Natural leather materials have a hierarchical structure and elemental composition similar to human skin; thus, they can be used as an excellent substrate material for flexible sensors. To date, various leather composites have been widely used in flexible sensors, which can be divided into different working mechanisms, including piezoresistive sensing^[13,16], strain sensing^[58,59], triboelectricity^[17,21], and so on. Ma *et al.* prepared AgNW/leather composites and assembled them with interdigitated copper electrodes to form a piezoresistive sensor [Figure 3Aa]^[41]. The piezoresistive sensor showed different sensitivities in three distinct pressure stages, indicating excellent piezoresistive sensing ability. When the pressure is lower than 2.5 kPa (stage I), the piezoresistive sensor shows a low sensitivity due to the slight compression deformation of AgNW/leather composites. As the pressure increases to 10 kPa (stage II), the collagen fiber bundles undergo densification, resulting in a more efficient conductive network under larger compression deformation, so the piezoresistive sensor shows a high sensitivity. If the

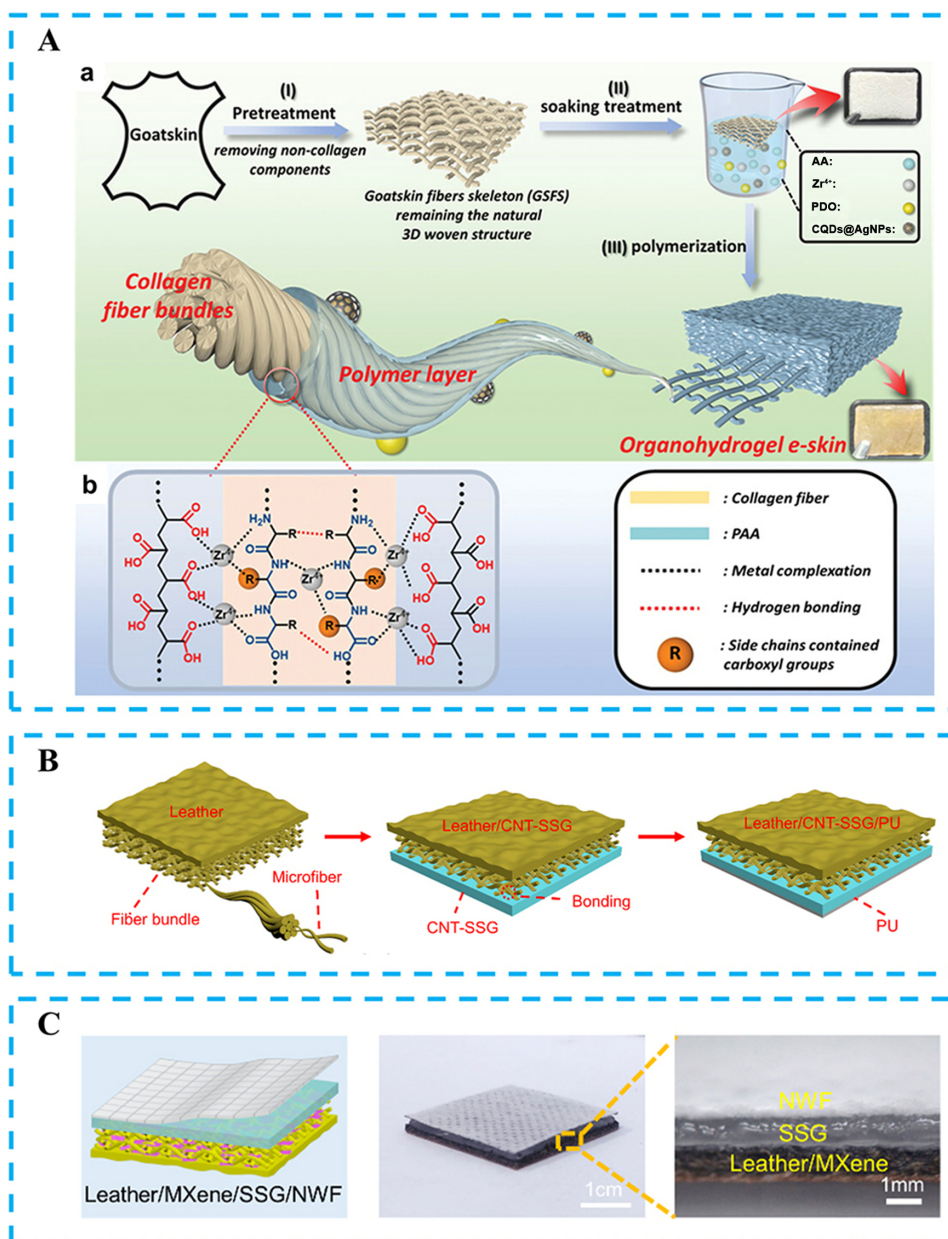


Figure 2. The preparation methods of leather composites. (Aa) Schematic fabrication route of leather composite by *in-situ* polymerization; (Ab) the crosslinking mechanism of leather composite^[27]. Reprinted with permission. Copyright 2023, Wiley-VCH; (B) The schematic of Leather/CNT-SSG/NWF; and (C) Leather/MXene/SSG/NWF by multilayer assembly^[53,54]. CNT: Carbon nanotube; SSG: shear stiffening gel; NWF: nonwoven fabric.

applied pressure is larger than 10 kPa (stage III), the sensitivity of the piezoresistive sensor begins to decrease because the efficient conductive networks have been constructed [Figure 3Ab and c]. Furthermore, the sensing performance of AgNW/leather composites is stable under multiple pressure cycling current changes and has a short response time (100 ms) [Figure 3Ad and e]. The leather pressure sensor can also monitor finger bending and changes in the throat during speech in real-time, demonstrating excellent responsiveness and stability in human motion detection [Figure 3Af-h].

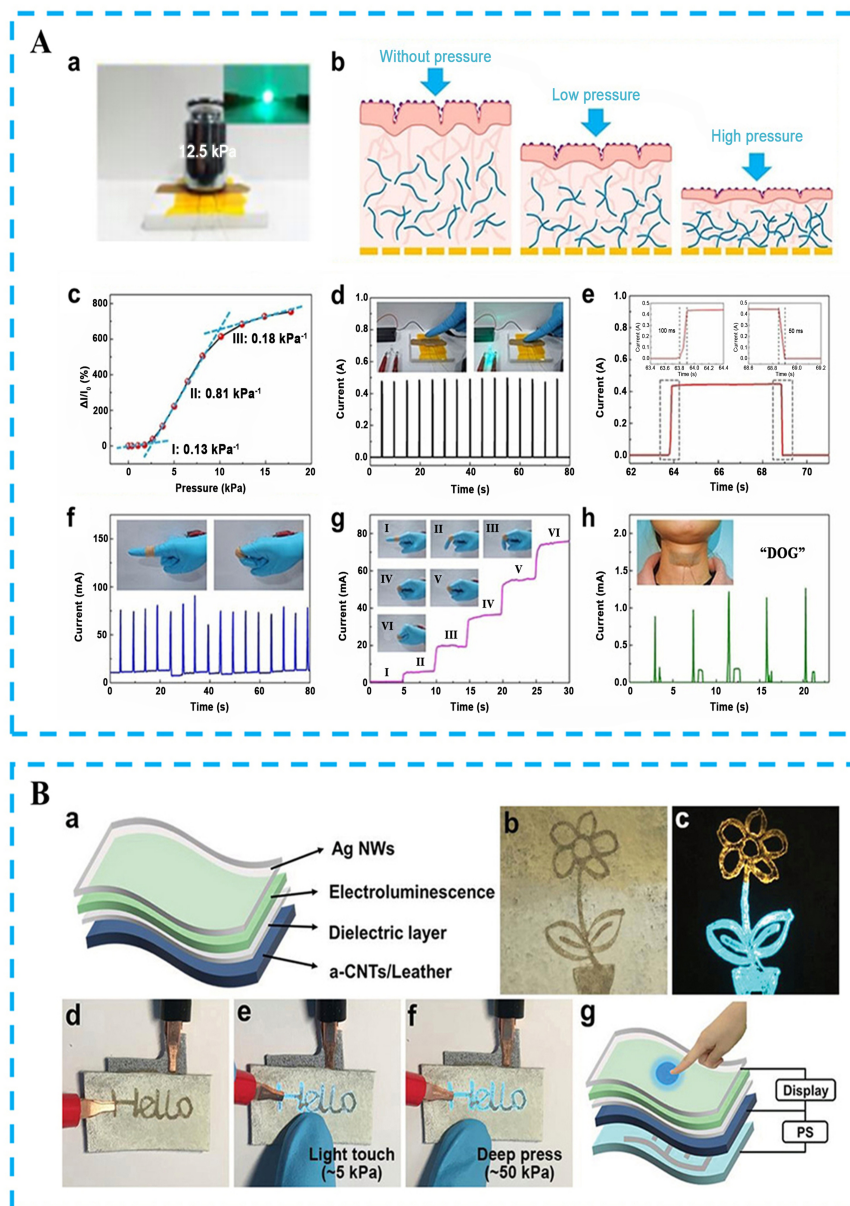


Figure 3. The application directions of leather composites. (Aa) The LED lamp lighting upon pressure; (Ab) illustration for the electric current response mechanism upon externally applied pressures; (Ac) relative current changes of the AgNW/leather nanocomposites upon various pressures, (Ad and e) the piezoresistive sensing performances of the AgNW/leather nanocomposites; (Af-h) human motion detection of the AgNW/leather nanocomposites^[41]. Reprinted with permission. Copyright 2022, Wiley-VCH; (Ba) Structure of leather-based display; (Bb-g) smart display based on electroluminescence^[42]. Reprinted with permission. Copyright 2019, Wiley-VCH. AgNW: Silver nanowire; CNT: carbon nanotube.

Actually, fabric-based flexible electronics also have good sensing performance; however, their mechanical strength is weaker than the leather composites^[60]. Yan *et al.* prepared a polytetrafluoroethylene (PTFE)/AgNW/silk fibroin fabric sensor, and it showed wonderful monitoring^[61]. Obviously, its application can be enlarged after improving the low tensile strength. Xie *et al.* introduced carbon black into leather, and then the Kirigami structure was designed^[58]. The leather-based strain sensor can accurately identify the bending angle and direction. More importantly, the resistance changes maintained the stability of the strain sensor under 12,000 bending cycles, which showed good durability and mechanical performance. Finally, the shapes also can be recognized by using this sensor. Due to the unique surface structure of leather, the rough

fiber surface provides natural advantages for frictional power generation. Moreover, Zhang *et al.* constructed rough MXene films on leather fiber surfaces to improve the performance of frictional power generation. The output voltage of the leather-based triboelectric nanogenerator (TENG) was stable under cyclic impact for 4,000 s, which showed excellent durability. Furthermore, the array sensor was fabricated to achieve the motion control of a mechanical hand, which demonstrated the potential in human-computer interaction applications^[21].

With the development of intelligent leather composites, conductive leather is widely used in various industries^[30]. By utilizing the sensing capabilities of conductive leather, “dead skin” is “revitalized”, providing a new electronic device design strategy for intelligent sensing, display, and interaction devices^[42]. In the dyeing and finishing process of leather making, personalized design is carried out on leather composites to obtain multi-stimuli responsive chromic devices^[62]. Zou *et al.* applied an electroluminescent layer on the surface of the conductive leather composite and successfully illuminated them by designing complex patterns such as flowers and words, demonstrating the excellent visual display ability of electronic devices^[42]. Furthermore, the brightness of leather-based electronic devices could be varied with the amount of pressure applied, which further controlled the light intensity of the device through pressure and provided real-time visual feedback [Figure 3B]. This design strategy is simple and efficient; thus, it is expected to be intensively applied to develop artificial intelligence and interactive electronic devices.

Electromagnetic interference shielding

With the popularization of electronic devices, concerns about electromagnetic radiation pollution and electromagnetic shielding have become important^[31]. Generally, the main ways to shield electromagnetic waves include reflection, absorption, and multiple reflections^[63]. It is beneficial for enhancing the electromagnetic shielding effect by designing the structure and conductivity of the material. Leather has the natural dielectric property, which enables dipoles to relax, resulting in dielectric loss to electromagnetic wave energy under the action of electromagnetic waves^[43]. Secondly, after functionalization by various conductive materials, the 3D collagen fiber network of the leather will induce electromagnetic waves to undergo multiple reflections in the conductive network, resulting in Ohmic loss to consume electromagnetic wave energy. For example, Bai *et al.* used polypyrrole (PPy), superconductive carbon black (SCB), 1H, 1H, 2H, 2H-perfluorodecyltriethoxysilane (PFDTES), and PDMS to nano-engineer the design of leather^[64]. The resulting PPy/SCB@PP-CFs with high conductivity (6.5 S/m) show significant electromagnetic shielding ability [Figure 4A]. It also indicates that the thickness of leather composites is positively correlated with electromagnetic shielding performance. As the thickness increases, the time for multiple reflections of electromagnetic waves on leather increases; then, more electromagnetic wave energy is consumed. At the same time, leather, as a promising natural material, has excellent X-ray protection capabilities due to its multilayer woven structure that complements other functional materials^[65-67].

Flame retardant

Leather is inherently flammable since it is composed of a large number of collagen fibers and contains elements such as carbon, nitrogen, hydrogen, and oxygen^[68], which limits its applications. Therefore, it is very important to develop leather composites with flame-retardant properties^[69]. Recently, many intelligent fire-safe fabrics have been developed by modifying the surface of textiles with flame retardants^[70-72]. The preparation of leather requires tanning and fat-liquoring, which greatly facilitates the addition of flame retardants and can be directly introduced into the leather-making process^[73]. Wang *et al. in situ* grew silica particles on the 3D framework of leather and sprayed silica particles on the surface to obtain a thermal insulation layer^[37]. The leather composite did not ignite after direct contact with the flame, demonstrating its excellent flame retardancy [Figure 4B]. Lyu *et al.* added montmorillonite and layered double hydroxide to leather during the fat-liquoring process to form a synergistic flame retardant system that enhances the

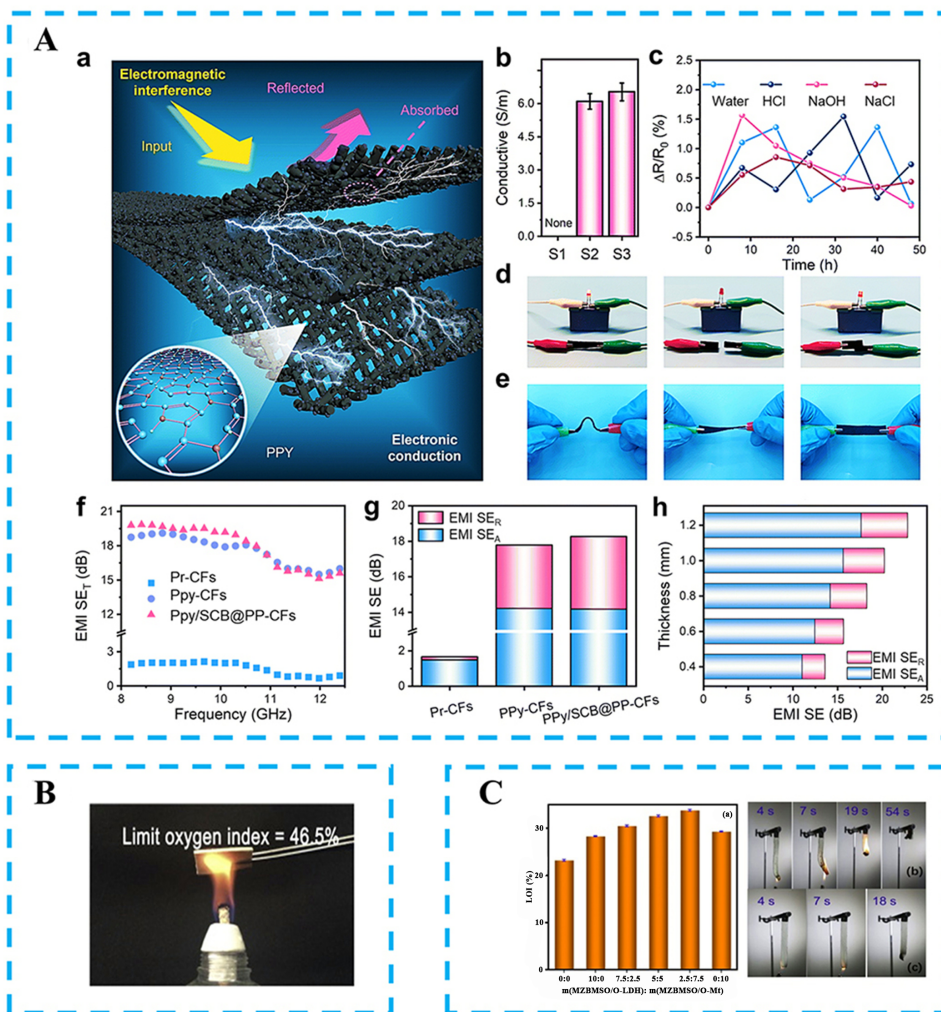


Figure 4. The application directions of leather composites. (Aa) Schematic illustration of electromagnetic interference shielding and electronic conductivity of PPy/SCB@PP-CFs; (Ab-e) the characterization of electrical characteristics; (Af-h) the EMI effectiveness of PPy/SCB@PP-CFs^[64]. Reprinted with permission. Copyright 2023, Royal Society of Chemistry; (B) and (C) The flame retardant performance of leather composites^[25,37]. Reprinted with permission. Copyright 2018, Elsevier. Reprinted with permission. Copyright 2021, Elsevier. PPY: Polypyrrole; SCB: superconductive carbon black.

protection of leather fibers^[25]. The ultimate limiting oxygen index of leather composites reaches 33.8%, and leather composites can quickly self-extinguish after leaving the flame, greatly improving the fire safety of leather [Figure 4C].

Safeguarding

Leather was used as a popular armor material in ancient times, but its protective performance had not been further improved as time went by^[74]. Considering its wear resistance and mechanical strength, the development of leather composites with excellent protective properties has gradually attracted attention^[24]. Surianarayanan *et al.* treated leather with silane to improve its load distribution and impact resistance, which enabled leather composite to absorb more impact energy^[75]. The multilayer structure assembled by leather composites greatly improves its load-bearing and fatigue performance. Fan *et al.* used a rate-dependent SSG to strengthen the natural leather, and then the cold flow effect of SSG allowed it to penetrate slightly into the porous structure of the leather, resulting in a flexible-tough coupled leather composite. It

exhibits excellent impact resistance under different impacts^[53]. More recently, to enlarge its application, the leather layer was treated by MXene nanosheets for functional design. The treated leather composite has excellent conductivity and no reduced impact resistance^[54], which can provide sensing feedback under different impacts. Finally, an intelligent impact resistance device based on the wearable Leather/MXene/SSG/NWF safeguarding leather composite was obtained by integrating a wireless transmission system; therefore, the final system could monitor the impact status of the leather composite in real time [Figure 5A]. In short, the development of intelligent leather composites opened up new avenues in the field of intelligent protection.

Thermoregulatory clothing

Recently, many studies have reported the development of multifunctional textiles for intelligent thermoregulation, which could maintain human body temperature in a comfortable area^[76]. Most animal fur benefits from the low thermal conductivity brought by their multilayer and porous skin structure; thus, they can effectively reduce heat loss and have a natural insulation effect^[37]. In this case, the most common use of leather in daily life is in the field of clothing^[5]. It is worth noting that during sudden changes in weather or harsh environments, a single insulation performance may not be able to meet the temperature needs of the human body^[77]. Mo *et al.* developed an asymmetric double-layer leather composite. A porous cellulose acetate layer achieved passive radiation cooling on the corium side, and a highly connected CNT network exerted passive radiative heating and Joule-heating ability on the other side^[45]. The two different functions can switch between cooling and heating modes according to environmental conditions by turning over two sides of the fabric, thus achieving high adaptability to weather changes [Figure 5B]. Fan *et al.* designed a conductive MXene array on a leather substrate, resulting in a leather vest that could achieve regional electric heating^[54]. By controlling voltage, the leather vest could precisely regulate the temperature regulation, which could be used to cope with extreme cold environments by providing the required temperature for the human body [Figure 5C]. As a result, the above analysis demonstrates that the leather composites exhibit enormous application potential in intelligent thermoregulatory clothing.

SOFT WEARABLE ROBOTICS FOR FUTURE APPLICATIONS BASED ON LEATHER COMPOSITES

In recent years, soft wearable robotics has received increasing attention due to the rapid development of flexible sensors and human-robot interface applications^[78]. Xiloyannis *et al.* developed a soft and textile-based robotic exoskeleton for assisting hand opening and closing [Figure 6A]^[79]. Schmidt *et al.* introduced a soft and wearable device to provide gravity support to the user's knee and hip joints [Figure 6B]^[80]. These resulting soft robotic devices based on textiles could help the wearer engage in simple daily activities. Leather composites have good biocompatibility and natural fiber structure, but research on the application of soft robots is scarce. Dong *et al.* prepared a smart conductive leather skin to imitate the functions of human skin^[50]. Furthermore, a smart glove based on leather skin was designed to monitor complex hand movements. At the same time, a human-computer interaction function has been developed based on the smart glove, which can control the movement of the robotic arm in real time by using gestures [Figure 6C and D]. A broad research foundation of leather composites has been built in intelligent applications. Intelligent leather composites will expand their research gaps in the field of soft robots in the future by combining their biocompatibility and mechanical strength. Ultimately, it is expected to develop soft robots that can cope with different complex environments, such as biomimetic soft robots, radiation-resistant robots, safety protection robots, *etc.*

CONCLUSION AND OUTLOOK

Natural leather has a unique multilayer structure and collagen fiber network, which is easy to combine with

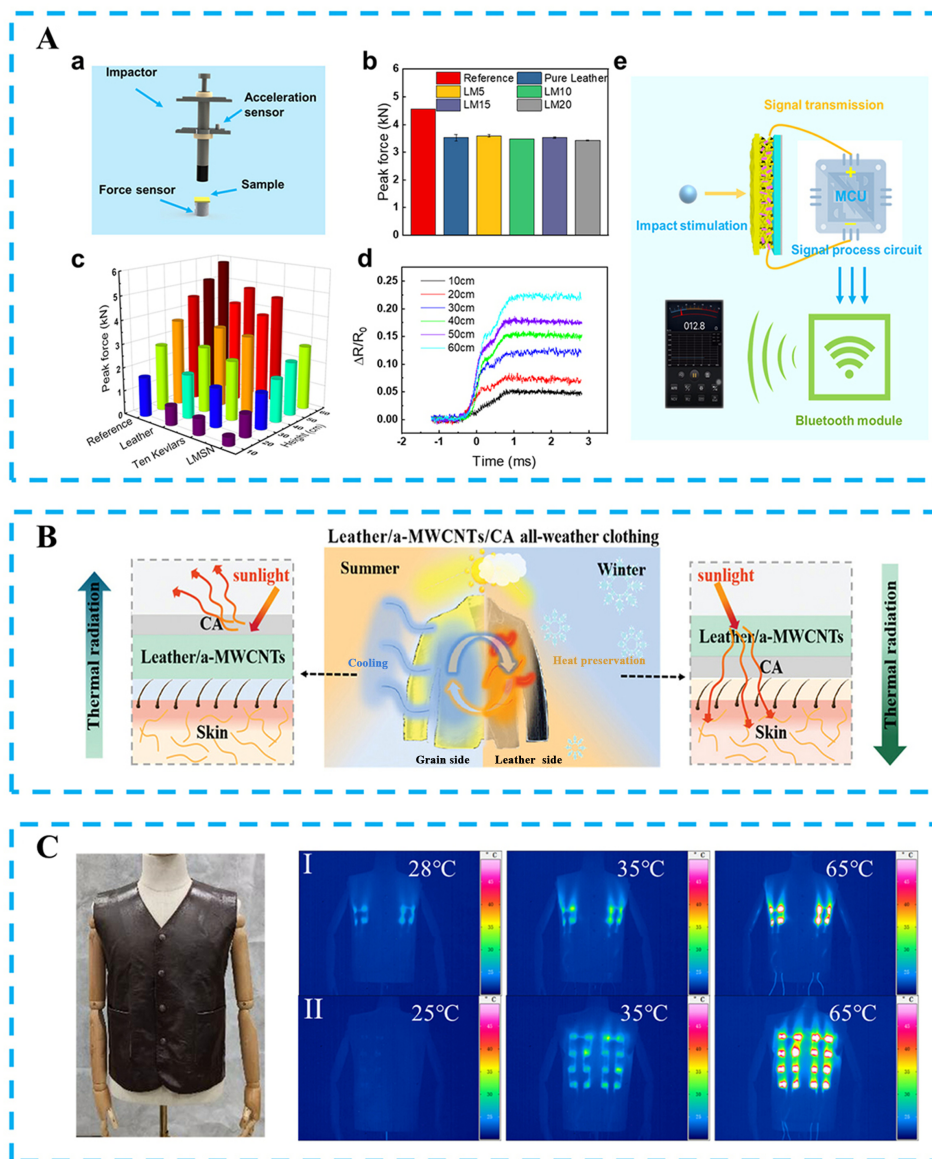


Figure 5. The application directions of leather composites. (A) The impact-resistant and impact-sensing performances of Leather/MXene/SSG/NWF^[54], (B) The cooling and heating modes of leather/a-MWCNTs/CA all-weather fabric^[45]. Reprinted with permission. Copyright 2023, Wiley-VCH; (C) The optical image and IR camera images of intelligent thermoregulatory clothing^[54]. SSG: Shear stiffening gel; NWF: nonwoven fabric; a-MWCNTs: acidified multiwalled carbon nanotubes.

various functional materials, taking advantage of each other to obtain soft, wear-resistant, and editable intelligent leather composites. This perspective reviews the recent research progress of leather composites, summarizing and analyzing the existing preparation methods of leather composites. Furthermore, this work also emphasizes various popular application directions based on the different functionalities of leather composites, such as flexible sensors, electromagnetic interference shielding, flame retardant protection, impact-resistant safety protection devices, and intelligent thermoregulatory clothing. In addition, although great application prospects have been achieved on leather composites, there are still significant difficulties and challenges in practical applications.



Figure 6. The application of soft wearable robotics. (A) Soft robotic glove for grasping assistance^[79]. Reprinted with permission. Copyright 2017, SAGE; (B) The Myosuit for supporting the user's knee and hip joints. Reprinted with permission. Copyright 2017, Frontiers Media^[80]; (C) Schematic diagrams of the smart glove and its controlling circuits and (D) various hand gestures of smart gloves in real-time^[50]. Reprinted with permission. Copyright 2017, Elsevier.

Firstly, economical, environmentally friendly, safe, and efficient functional materials can be developed to reduce the production cost of leather composites and promote their faster application from the source. Secondly, it is necessary to strengthen the stability and durability of leather collagen fibers combined with functional materials, maintaining the breathability and comfort of leather to ensure the stable performance and advantages of leather composites during the application process. Thirdly, the preparation process of leather composites should be improved. The filtration, spraying, *in-situ* growth, and other methods of the leather-making process should be industrialized, mechanized, and simplified so that intelligent leather composites can embark on the path of industrialization. Fourthly, specific performance in the application direction can be further deepened. Intelligent leather, such as conductive leather, flame-retardant leather, and electromagnetic shielding leather, should be developed toward similar industry standards, and a

performance standard system for functional leather can be established to standardize production and performance standards. Finally, developing multifunctional sensing for leather composites can enable leather to perceive the world similarly to human skin by combining machine learning to carry out human-computer interactions.

In conclusion, as an emerging flexible intelligent biomaterial, leather composites have demonstrated enormous potential for various applications, especially in the fields of sensing and safety protection. This coincides with the safety and real-time sensing of some soft robots in hazardous environments. Therefore, leather composites can be developed towards biomimetic, intelligent, and thermo-mechanical coupled safety protection in the future. It is believed that this result can open up new research directions for the design and safe use of soft robots.

DECLARATIONS

Authors' contributions

Wrote the original draft: Fan Z, Sang M

Supervised, reviewed, and revised the manuscript: Leung KCF, Gong X, Xuan S

Availability of data and materials

Not applicable.

Financial support and sponsorship

Financial support from the National Natural Science Foundation of China (Grant Nos. 12072338, 12132016, and 12202435), the Anhui's Key R&D Program of China (202104a05020009), the Aviation Science Foundation of China (20200029079004), the Fundamental Research Funds for the Central Universities (WK2480000007) is gratefully acknowledged.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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