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Review

Recent progress in low dimensional carbon nanomaterials sensors and their integration with artificial intelligence technologies

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Abstract: Carbon-based sensors based on low-dimensional carbon nanomaterials demonstrate broad application prospects in fields such as wearable devices and human–computer interaction, owing to the exceptional properties of carbon nanomaterials. Driven by advancements in artificial intelligence (AI) technology, these sensors are progressively evolving from single-function devices into intelligent systems. This article highlights five types of AI-oriented carbon-based sensors, discussing the integration and application of artificial intelligence with carbon-based sensing technology. To address challenges like insufficient external information acquisition capability and system redundancy caused by the separation of sensing and computation, we introduce the multimodal sensing system and the sensing-computation integrated architecture: the former enhances information dimensionality through collaborative perception of multiple physical signals, while the latter seamlessly integrates signal acquisition with intelligent processing. Ultimately, AI-empowered carbon-based sensing systems not only improve perception accuracy and processing efficiency but also establish the foundation for autonomous intelligent sensing systems, demonstrating substantial prospects for next-generation smart hardware.

Keywords: carbon-based sensors; artificial intelligence; multimodal sensing system; sensing-computation integrated architecture

1. Introduction

In recent years, artificial intelligence (AI) technology has advanced at an unprecedented pace, driving efficiency transformations across various industries [1–4]. With its powerful data processing and analytical capabilities, AI can uncover patterns from massive datasets and make informed decisions, poised to propel humanity into the Fourth Industrial Revolution [5]. From real-time vital sign monitoring in healthcare to environmental parameter adjustment in smart manufacturing, the precision of AI systems heavily relies on front-end sensors' ability to capture and transmit complex information. Carbon-based sensors, relying on their unique material properties and performance advantages, have emerged as a critical solution to meet these demands, providing a robust perceptual foundation for the deep integration of AI technology.

Constructed around carbon nanomaterials, carbon-based sensors benefit from exceptional electrical, thermal, and mechanical properties. Graphene exhibits ultrahigh electron mobility, superior thermal conductivity, and mechanical strength [6]. This is because the sp^2 hybridized carbon atom structure forms a delocalized π electron cloud, endowing it with high conductivity and mechanical strength [7]. Carbon nanotubes are one-dimensional tubular structures with extremely high aspect ratios that can produce significant resistance changes even under low strain, thereby contributing to high sensitivity [8,9]. Nanocarbon, as a zero-dimensional quasi-spherical carbon nanoparticle, can effectively fill gaps in composite materials and form a synergistic conductive structure with other dimensions of carbon materials [10]. Sensors fabricated from these materials demonstrate high sensitivity, rapid response times, and excellent stability [11], showcasing significant application potential in sensing fields.

In addition, various methods can be used to better regulate the performance of sensors based on existing low-dimensional carbon nanomaterials, such as doping chemicals to enhance the internal conductive network [12], and designing microstructures to optimize the conductive mechanism [13].

We have collected various cases of combining low-dimensional carbon nanomaterial sensors with artificial intelligence. These cases are summarized as follows:

In the field of stress sensing, sensors based on low dimensional carbon nanomaterials are now embedded within wearable systems capable of continuously tracking micro-deformations such as pulse or joint flexion. Through AI-assisted temporal decoding, these sensors enable precise assessment of human movement, fatigue levels, and even gesture-based human-computer interaction [13]. In addition, carbon-based stress sensors can also be applied in the fields of speech recognition [14].

In the field of acoustic sensing, graphene-based sensors exhibit high sensitivity and excellent ductility, characteristics enabling the development of ear health monitoring systems. Integration with convolutional neural network (CNN) significantly enhances the accuracy of acoustic data processing [15]. Besides, carbon-based acoustic sensors can achieve ultrahigh accuracy recognition of individual pronunciations through a small number of units [16].

In the field of thermal sensing, carbon-based temperature sensors have evolved from simple temperature monitors into intelligent health diagnostic platforms, owing to their high thermal conductivity and skin-conformable structures. Recent studies have leveraged deep neural networks for real-time detection of temperature-related diseases [17]. In addition, by constructing composite carbon-based temperature sensors, environmental humidity can also be detected [18].

In the field of optical sensing, the inherent broadband absorption and ultrafast carrier mobility of carbon nanostructures have expanded the role of optical sensors from basic photodetection to intelligent visual processing platforms. Rapid advancements in machine learning capabilities have empowered integrated imaging systems developed using graphene photodetector arrays with object tracking functionality and image denoising [19,20].

In the field of brain-computer interfaces (BCIs), carbon-based neural interface materials, such as graphene electrodes, are at the forefront of decoding complex electrophysiological signals. Complex electrophysiological signals are usually obtained by neural interfaces through electrochemical sensing techniques such as cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). When paired with AI algorithms, these interfaces transcend mere raw signal recording and are designed for noninvasive treatment of cognitive disorders [21] and neuromodulation [22]. In addition, carbon-based wearable neuromorphic systems can also achieve monitoring of human health status [23].

The combination of carbon-based sensors and AI technology has made significant progress in the above five fields. However, based on the limitations of single-modal sensors in complex environments and the issues of high energy consumption and limited computational capacity inherent in the traditional von Neumann architecture, this article proposes future development directions for carbon-based sensor–AI systems: multimodal sensing systems for diverse physical parameters and integrated sensing-computing analytical systems.

This article explores recent advances in the integration of carbon-based sensors and artificial intelligence, highlighting the pivotal supporting role of carbon nanomaterials in enabling high-fidelity, multimodal perception. Carbon-based materials—including graphene and carbon nanotubes (CNTs)—provide a robust foundation for constructing highly sensitive, flexible, and wearable multifunctional sensors, owing to their exceptional electrical, thermal, and mechanical properties. Concurrently, the introduction of AI algorithms, particularly machine learning and spatiotemporal signal processing techniques [24], has significantly enhanced the resolution, specificity, and robustness of sensing systems. Such integration aims to achieve adaptive learning, low-power real-time decision-making, and multimodal collaborative sensing. As shown in Figure 1, the combination of carbon-based sensors and AI technology will play a significant role in the future intelligent society.

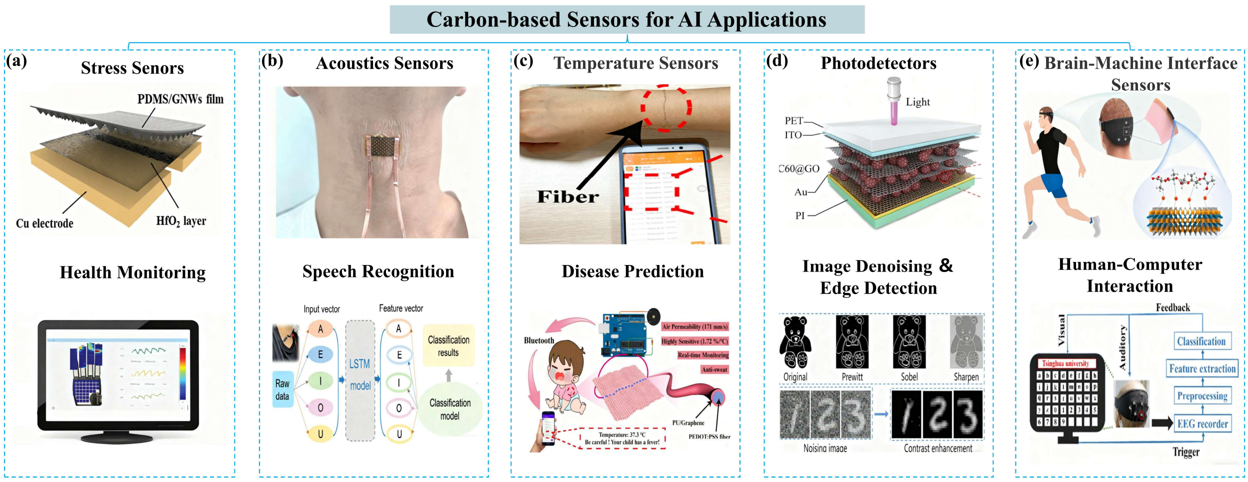

Figure 1. An overview of carbon-based sensor devices for artificial intelligence applications. (a) Stress sensors and health monitoring (Reproduced from Ref. [25] with permission). (b) Acoustics sensors and speech recognition (Reproduced from Ref. [26] with permission). (c) Thermology sensors and disease prediction (Reproduced from Ref. [27] with permission). (d) Optical sensors and image denoising & edge detection (Reproduced from Ref. [28] with permission). (e) Brain-machine interface sensors and human-computer interaction (Reproduced from Ref. [29] with permission).

2. Carbon-based sensors

2.1. Carbon-based stress sensors

Taking stress sensors as an example, carbon-based sensors exhibit superior performance compared to sensors made from other materials in multiple aspects. They feature high sensitivity, wide tensile range, long lifespan, and high linearity. This demonstrates that carbon-based sensors hold broad application prospects in fields such as flexible electronics, wearable devices, and human motion monitoring. Typical performance comparisons are systematically summarized in Table 1.

Table 1. Performance comparisons of carbon-based stress sensors versus stress sensors made from other materials.

Materials	Gauge factor/sensitivity	Max strain range	Response time (s)	Durability (cycles)
Carbon-based sensor: CNTs/PDMS/MoS_2 [30]	3528	55%	0.1	>1040
Carbon-based sensor: graphene/CNTs [31]	19.8 kPa^{-1}, <0.3 kPa	-	<0.167	35,000
Metal-based sensor: gallium [32]	7.42 kPa^{-1}, 0–0.1 kPa	-	0.054	10^4
Metal-based senor: Ag nanowire [33]	1.62 MPa^{-1}, <500 kPa; 0.57 MPa^{-1}, >500 kPa	50%	0.04	-
Silicon-based sensor: Si nanowire [34]	91.2	3.3%	-	3×10^3
Conductive polymer sensor: hydrogel [35]	4.07	300%	-	2×10^3

The integration of artificial intelligence has propelled sensing systems from simple strain detection toward higher-level perception. Unlike traditional strain-sensing systems that rely solely on analog signal amplitude, machine learning algorithms integrated with stress sensors can extract temporal, spatial, and frequency-domain features from signals. These systems further enable classification, prediction, and dynamic modeling of complex stress states, extracting high-dimensional features from dynamic stress signals in real time. This capability facilitates deeper semantic understanding of human motion [36], physiological states, and external stress environments.

Wei et al. have developed a graphene-based tactile sensor array based on a pressure-sensitive tunneling mechanism [25]. As shown in Figure 2a–d, this array achieves high spatial resolution (64 points/cm^2), high sensitivity (222.36 kPa^{-1}), and extremely short response time (2 milliseconds) based on a graphene nanowalls (GNWs) micro pyramid structure. By leveraging the array's high-resolution characteristic, the team successfully captured comprehensive pulse signals and precisely reconstructed the three-dimensional waveform of the pulse wave. This research demonstrates the significant potential of carbon-based sensors in the field of remote intelligent diagnostics.

Liang et al. designed a high-performance graphene strain sensor exhibiting a broad strain response range (0.2%–370%), with a high gauge factor (971.70), while maintaining excellent deformation stability [26], as shown in Figure 2e–g. This is mainly due to the use of the styrene butadiene rubber (SBR)@silica janus nanoparticles, which have both soft and hard sides and can form a variable and structurally stable uniform network with styrene butadiene rubber, which enhances the primary performance of the sensor. By integrating this sensor with machine learning models, the system achieves accurate recognition of five vowel sounds. This research expands applications for carbon-based sensors in silent speech recognition and voice-controlled systems.

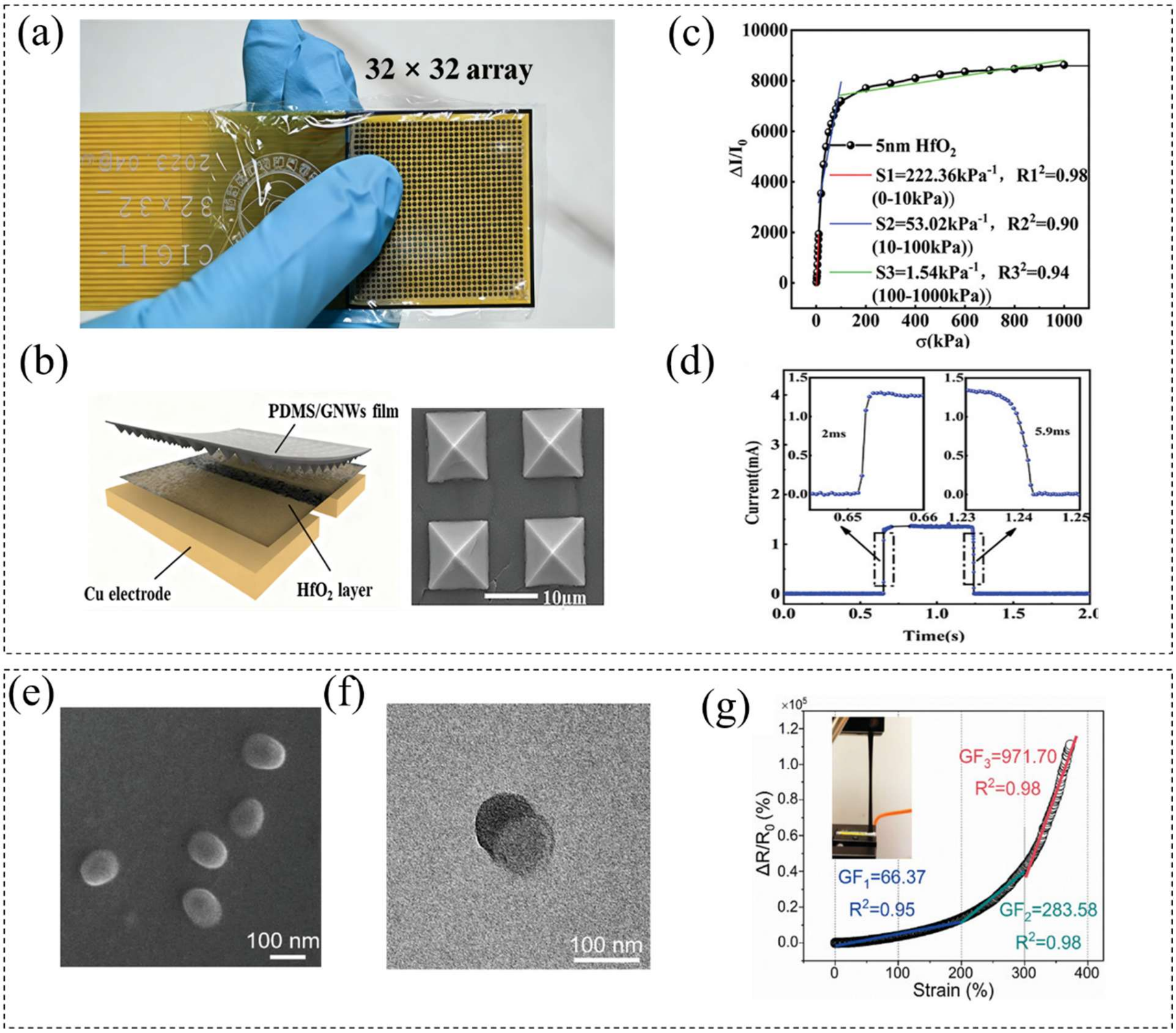

Figure 2. (a) Sensor array. (b) Schematic illustration of a tactile sensor cell and a scanning electron microscope (SEM) image of conformal GNWs on micro-pyramidal structures. (c) Normalized current versus pressure curves of the sensor. (d) Response/recovery times of the sensor (Reproduced from Ref. [25] with permission). SEM images of (e) SBR@silica janus nanoparticles and (f) corresponding styrene butadiene rubber. (g) Curve depicting the relative resistance change of the strain sensor as a function of tensile strain (Reproduced from Ref. [26] with permission).

In subsequent research, a reference should be made to the sensor parameter design guidelines proposed by Okabe et al. regarding the regulatory effect of CNTs content and coating thickness on the inflection point of the resistance strain curve [37].

The above two research works are based on graphene to develop carbon-based sensors, but there are significant differences in the core sensing mechanism (pressure-sensitive tunneling effect versus strain resistance effect), key performance focus (spatial resolution and response speed versus strain range and sensitivity coefficient), and target application scenarios (remote medical diagnosis versus voice interaction), which respectively promote the functional expansion and scenario implementation of carbon-based sensors from different dimensions.

In addition to the research introduced above, how sensors can be combined with data processing and signal processing technologies is also an important research direction. Zeng et al. designed a carbon black/polyvinylidene fluoride (CB/PVDF) nanocomposite material sensor. It can capture static strain and high-frequency vibration signals and accurately identify ultrahigh frequency ultrasonic guided waves, solving the problems of poor adaptability and difficult capture of high-frequency signals in traditional rigid sensors [38]. Song et al. proposed an inflection point recognition algorithm based on the rate of change of the cumulative growth rate to address the nonlinear resistance–strain response of carbon nanotube sensors. Threshold customization was achieved by adjusting the coating thickness and CNTs content [37].

There are two main directions for the development of carbon-based stress sensors: on one hand, structural enhancement models such as graph neural network (GNN) can significantly improve the understanding of non-uniform, multi-source stress fields [39]; on the other hand, the integration of neuromorphic chips and low-power model compression technologies holds promise for achieving real-time, low-latency strain classification and feedback control. This drives the continuous evolution of stress-sensing systems toward greater intelligence, adaptability, and generalization capabilities [40,41].

At a more macro level, carbon-based stress sensors have very broad prospects, and structural health monitoring is a very important field. According to two studies by Zeng et al., carbon-based nanomaterials modifying cement-based materials were used as the core, and a conductive network constructed using carbon-based materials was used to achieve piezoresistive sensing (resistance changes with stress). At the same time, energy collection was achieved by relying on the frictional electrification effect between cement-based materials and polytetrafluoroethylene, and the performance stability of fully cured cement-based materials was verified, which is suitable for practical engineering application scenarios. Both studies focus on traffic monitoring and structural health monitoring as their core application directions, emphasizing the potential of devices in large-scale structural safety assurance in aerospace, construction, and other fields [42,43].

2.2. Carbon-based acoustic sensors

Acoustic-electric coupling sensors are propelling acoustic perception systems from signal conversion toward intelligent interaction. Unlike traditional acoustic sensors that merely achieve unidirectional sound-electricity conversion, intelligent sensing systems integrated with artificial intelligence technology can deeply mine the temporal waveforms, spectral characteristics, and mechanical vibration coupling patterns of acoustic signals. These systems accomplish speech semantic parsing, encrypted transmission, and anomaly pattern recognition, extracting high-dimensional information from sound wave vibrations to achieve precise understanding and proactive responses to human speech and environmental acoustic events.

Ren et al. developed a graphene-based intelligent wearable artificial throat (AT), achieving acoustic-electrical coupling sensing and multimodal AI integration [44]. This system simultaneously captures pressure and acoustic information while maintaining noise immunity. Experimental validation confirms its precise recognition of fundamental phonemic units. As shown in Figure 3a,b, leveraging an on-device AI model, the system successfully deciphered the majority of speech content from laryngectomy patients, overcoming the technical limitation of traditional artificial throats that rely on clear airflow vibrations. This pioneering work establishes a new frontier in speech interaction for patients with aphonia.

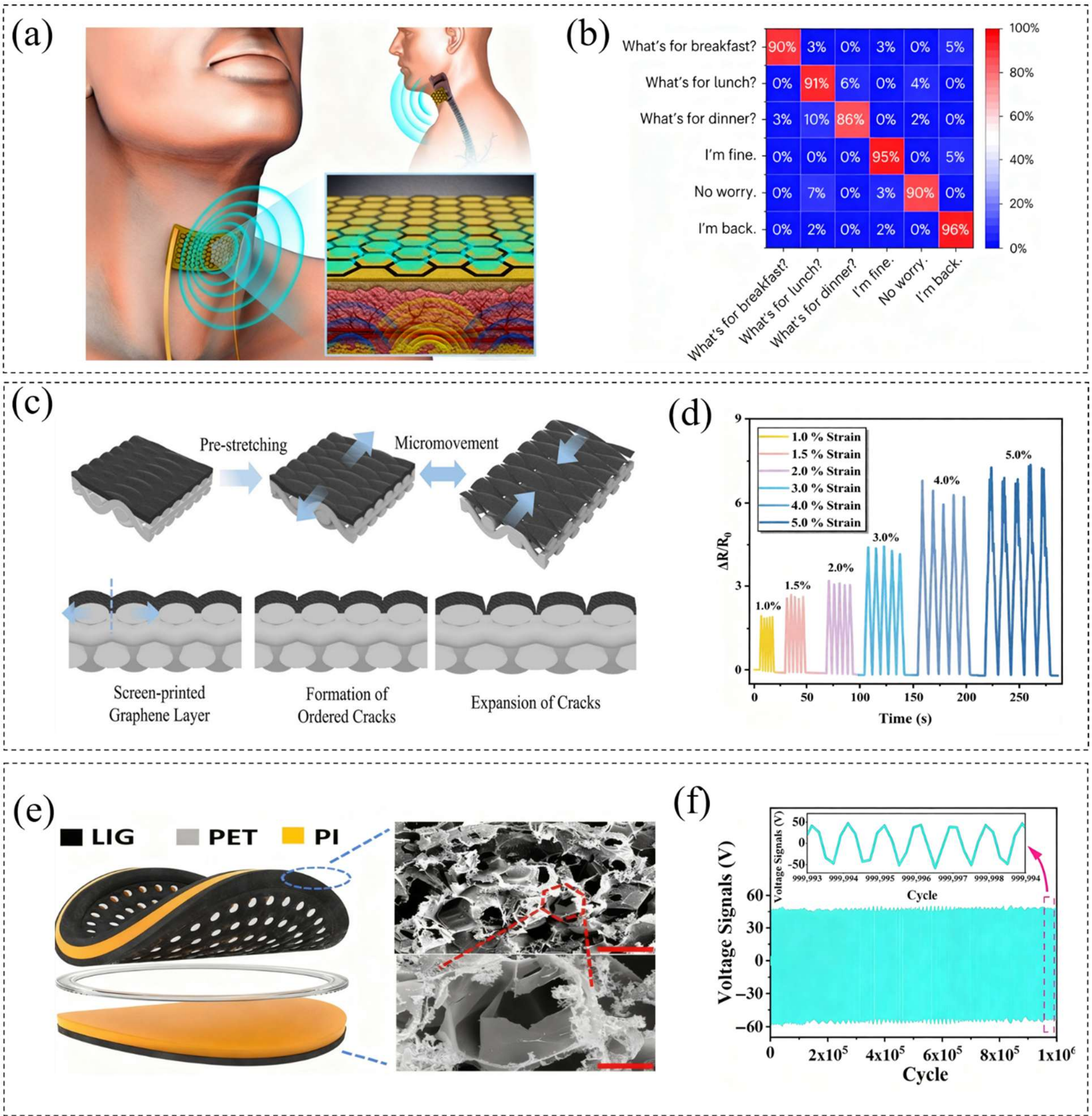

Figure 3. (a) Schematic diagram of the intelligent AT. (b) Confusion matrix generated by the ensemble model (Reproduced from Ref. [44] with permission). (c) Schematic diagram of the textile-based strain sensor. (d) Relative resistance responses with several cyclic strains (Reproduced from Ref. [45] with permission). (e) Structural diagram of the transducer and SEM of laser induced graphene (LIG). (f) Durability test of the acoustic transducer (Reproduced from Ref. [46] with permission).

Tang et al. developed a silent speech interface (SSI) by integrating the graphene sensing mechanism with artificial intelligence technology [45]. As shown in Figure 3c,d, this system achieved high-precision recognition, accelerated computational efficiency, and enhanced rapid decoding speed. It attained a gauge factor of 317 under small strain conditions, enabling it to detect subtle laryngeal movements. Furthermore, this sensor exhibited excellent cyclic characteristics under various small strain conditions. The neural network architecture based on a one-dimensional convolutional model significantly reduced computational power consumption while maintaining exceptional speech decoding accuracy.

Sun et al. proposed a graphene-based dual-functional acoustic transducer, achieving high sensitivity (4500 mV·Pa^{-1}) and exceptional operational durability (1 million cycles over 60 days) [46], as shown in Figure 3e,f. This device can identify human speech characteristics including biometric identification, emotional expression, and semantic content. Leveraging machine learning, it attained a peak detection accuracy of 99.66%. Furthermore, this research paves the way for advancing AI communication robotics through voice feature recognition.

Although the above three works belong to the field of voice interaction, their focus is completely different: while intelligent artificial larynx focuses on medical rehabilitation, providing silent speech recognition solutions for patients undergoing laryngectomy that do not rely on airflow, the silent voice interface is more suitable for high noise environments or communication scenarios that require privacy protection. On the other hand, Sun et al. research, with its ability to analyze multidimensional speech features, mainly focuses on future human–computer interaction, biometric recognition, and emotional AI robot systems.

Current research on acoustic electric coupling sensors focuses on the integration of new materials and mechanisms to enhance sensitivity and achieve self-powering. Existing technology is evolving from a single function of sound electric conversion to a multimodal intelligent perception system that can simultaneously perceive sound, pressure, and even temperature, and is beginning to integrate lightweight AI algorithms to achieve advanced functions such as speech recognition and identity verification. Its development trend is toward ultra-sensitivity, low power consumption, miniaturization, and intelligence, aiming to better serve cutting-edge fields such as wearable electronics, human–computer interaction, and the Internet of Things. The deep integration of acoustic-electric coupling sensors and AI will evolve toward cross-modal collaboration and adaptive learning. On one hand, neural networks leveraging attention mechanisms can enhance feature separation between acoustic signals and environmental noise, improving speech recognition robustness in complex sound fields [47]; on the other hand, combining sensor arrays with signal processing technologies is expected to enhance interaction response speed while protecting privacy, thereby driving acoustic-electric sensing systems toward smarter and more secure development.

2.3. Carbon-based temperature sensors

In the field of carbon-based temperature sensing, continuous technological innovations are driving its evolution from basic temperature detection toward intelligent health monitoring. Unlike traditional temperature sensing systems that rely solely on single thermosensitive elements, temperature sensing systems constructed with carbon nanomaterials can not only leverage the materials' excellent thermal conductivity and temperature-dependent electrical properties to achieve precise temperature measurement but also combine multidimensional data acquisition methods to extract characteristic parameters from dynamic temperature signals, enabling more refined quantitative analysis of human physiological states and environmental temperature variations.

Li et al. fabricated thermally responsive fibers using poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS) material with polyurethane (PU)/graphene encapsulation [27]. As shown in Figure 4a–d, these composite fibers demonstrated outstanding performance within the 30–50 °C sensing range, including high sensitivity (−1.72%/°C), fast response (17 s), ultrahigh resolution (0.1 °C), sweat resistance, and excellent linearity (R^2 = 0.98). This enables long-term, high-precision monitoring of human surface temperature, showing significant potential for applications in fitness monitoring and clinical care.

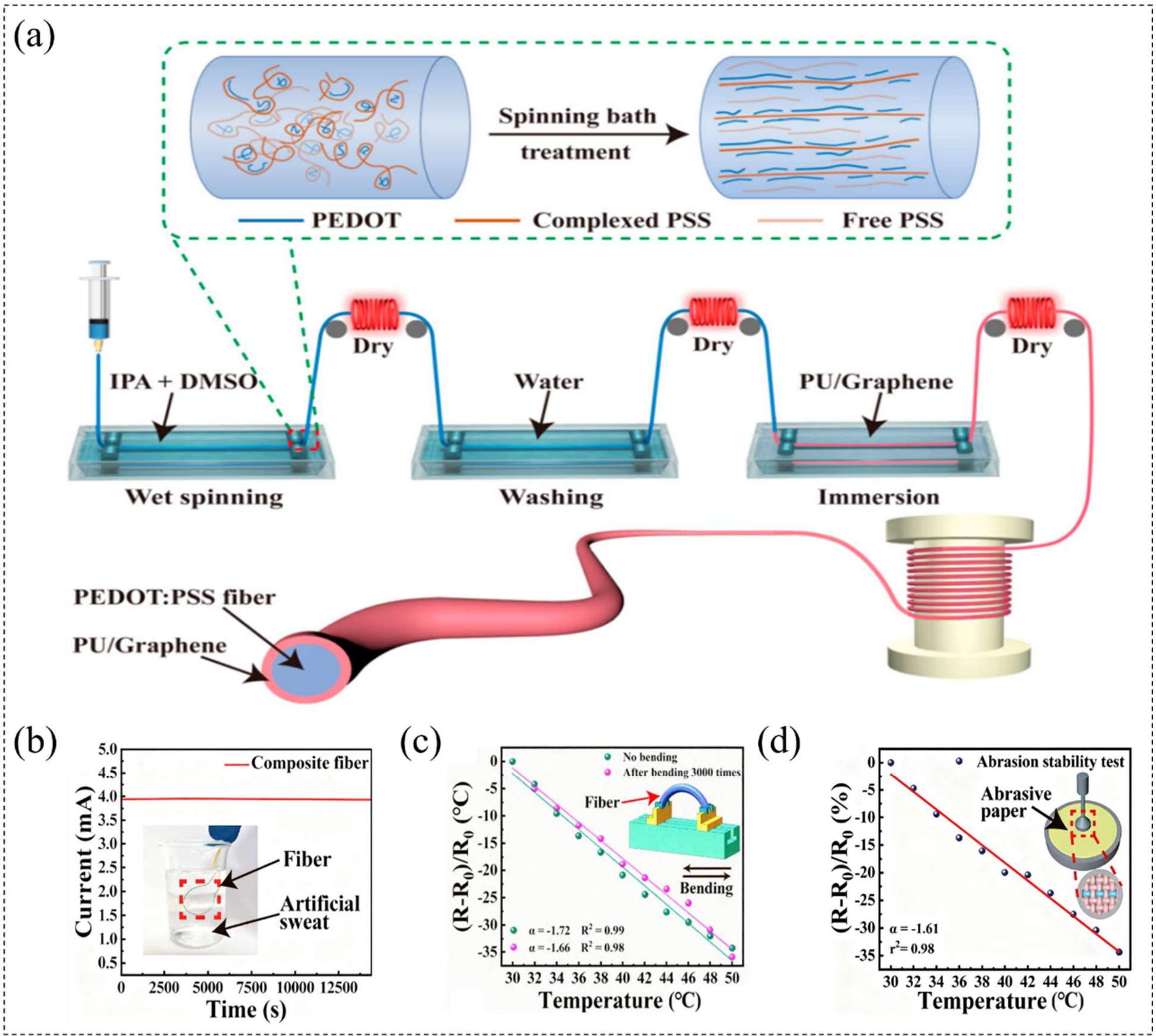

Figure 4. (a) Preparation diagram of the composite fiber. (b) Current stability of the composite fiber in artificial sweat. (c) Temperature-sensing stability of the composite fiber after bending. (d) Temperature-sensing stability of the composite fabric after rubbing (Reproduced from Ref. [27] with permission).

Current research on carbon-based temperature sensors has shifted from single temperature measurement to multifunctional integration and flexible wearable direction. By utilizing the advantages of materials such as carbon nanotubes, graphene, and carbon fibers, dual-mode sensors that can simultaneously monitor multiple signals such as temperature and pressure have been developed. These state-of-the-art designs are characterized by high sensitivity, fast response, and excellent stability through novel structural designs (such as core-shell structure and layered aerogels) and self-powered mechanisms (such as thermoelectric effects). Future development trends focus on improving environmental adaptability (such as suppressing interference through doping and structural regulation) and strengthening its integration with artificial intelligence. Through multivariate sensing and algorithms, these sensors achieve precise identification and classification of multiple analytes in complex environments, expanding its applications in health monitoring, electronic skin, and human–computer interaction.

The integration of carbon-based temperature sensors and artificial intelligence will advance toward intelligent health monitoring and multi-scenario adaptive perception. The next phase involves applying body temperature data collected by temperature sensors to machine learning models, where AI algorithms can perform real-time analysis and assessment of human health status. This enables a transition from temperature data acquisition to intelligent health diagnostics. On one hand, incorporating machine learning networks enhances the understanding of human body temperature fluctuation patterns, allowing more precise identification of potential health risks. On the other hand, integrating low-power models with portable devices holds promise for real-time, continuous personal health monitoring and early warning systems. This dual approach will propel carbon-based temperature sensing systems toward more intelligent and clinically valuable applications.

2.4. Carbon-based photodetectors

In the field of carbon-based photodetection, continuous technological innovation is driving its evolution from simple optical signal conversion toward intelligent information processing. Unlike traditional photodetectors that rely solely on single photoelectric conversion units, photodetection systems constructed with carbon nanomaterials can not only leverage their excellent optoelectronic properties—such as high light absorption coefficients and high carrier mobility—to achieve efficient optical signal conversion but also integrate multi-component devices to extract key characteristic parameters from complex optical signals. This enables more precise analysis of image information, optical communication signals, and ambient light variations.

Liu et al. prepared a uniform layered graphene oxide composite film [48]. As shown in Figure 5a,b, after integrating the bio-inspired optoelectronic synapse based on this film with CNN, it achieved 97.3% accuracy in dynamic visual recognition tasks.

Zhang et al. proposed a bionic retina based on carbon nanotube synaptic devices [28]. This enhanced signal processing and visual perception capabilities. By implementing a convolutional kernel algorithm on the artificial synapses, embedded edge detection and noise reduction functions were developed, significantly improving image recognition accuracy, as shown in Figure 5c–e. Furthermore, the system achieves motion direction discrimination and trajectory analysis, enabling direct application in robotic vehicle path planning.

Although both works focus on biomimetic visual perception and combine intelligent algorithms, their core materials and functional emphasis are different. The former strengthens dynamic visual recognition based on graphene oxide composite film, while the latter expands more complex functions such as visual signal processing and motion analysis through carbon nanotube synapse devices, providing differentiated biomimetic solutions for dynamic visual recognition and intelligent robot visual navigation.

The current research on carbon-based optoelectronic sensors mainly focuses on improving performance through heterostructure design and defect engineering, such as constructing graphene/silicon heterojunctions and regulating defect states, achieving wide spectrum and high responsivity detection from visible light to infrared bands. The characteristic of existing technology lies in utilizing the excellent optoelectronic properties of materials such as carbon nanotubes and graphene, combined with neural morphology architecture, to develop intelligent sensors that can integrate sensing, storage, and processing functions, significantly improving energy efficiency and reducing power consumption. Future development trends focus on multifunctional intelligence and flexible integration, accomplishing advanced functions such as optical logic computing and biomimetic audio-visual sensing, and promoting its application in cutting-edge fields such as flexible electronics and artificial vision.

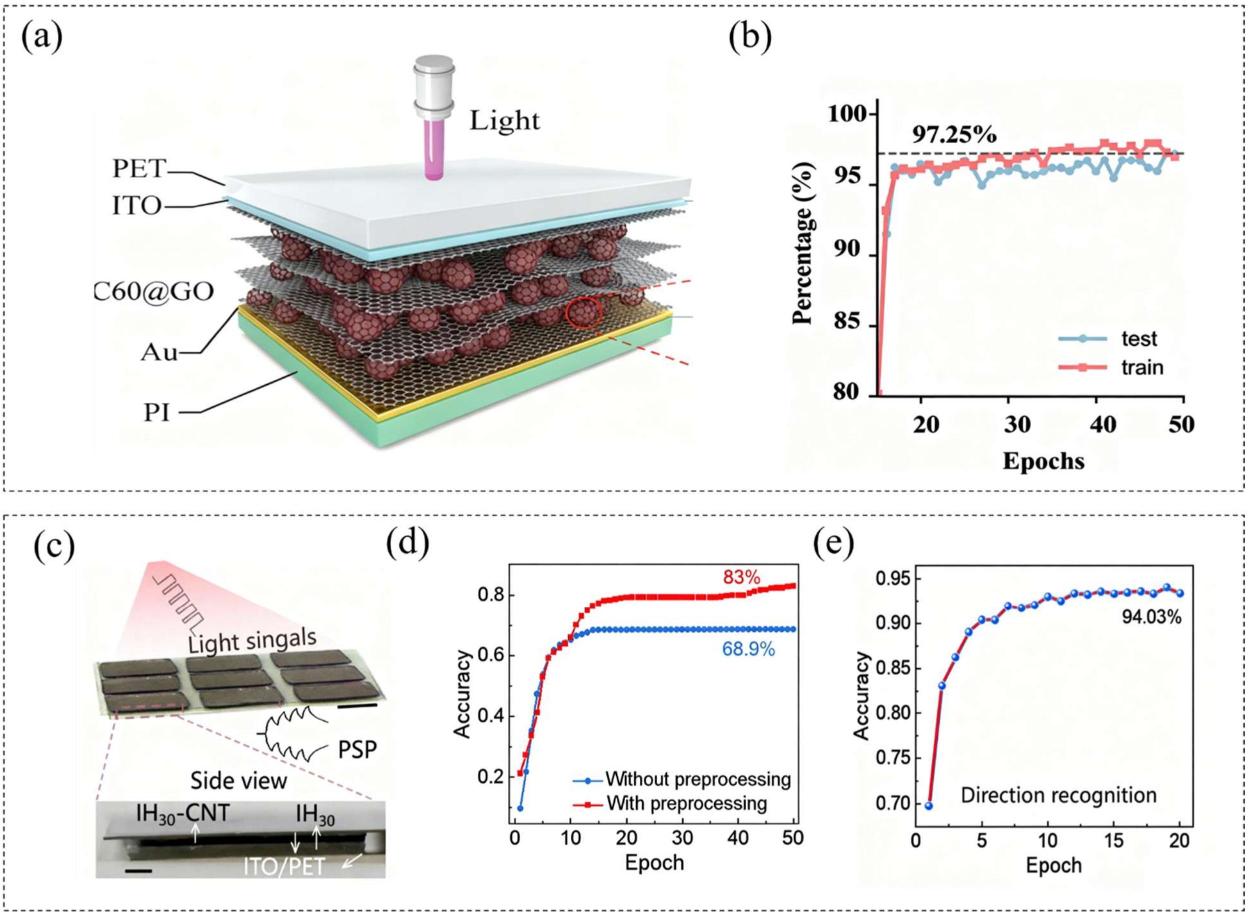

Figure 5. (a) Structural diagram of the photoelectric device and its partially enlarged internal view. (b) Training and test accuracy for datasets recorded in the same video classification task (Reproduced from Ref. [48] with permission). (c) Bio-inspired retina. (d) Recognition accuracies of the classifications of 0–9 images without and with preprocessing. (e) Direction recognition accuracy (Reproduced from Ref. [28] with permission).

The integration of carbon-based photodetectors and artificial intelligence will advance toward intelligent information processing and multi-scenario precision recognition. Current applications of carbon-based photodetectors in AI remain limited. Future development could feed optical signals collected by photodetectors into machine learning models to achieve image recognition and noise reduction functions, accomplishing the transition from optical signal conversion to intelligent information analysis and processing. On one hand, incorporating machine learning models will enhance understanding and processing capabilities for complex optical signals, enabling more precise execution of tasks like image recognition and signal denoising [20]. On the other hand, integrating low-power algorithms with portable detection devices holds promise for real-time and efficient intelligent optical information processing, implementing motion detection [49].

2.5. Carbon-based brain–machine interface sensors

In the field of carbon-based brain-computer interface sensing, continuous technological breakthroughs are driving its evolution from basic electroencephalogram (EEG) signal acquisition toward in-depth brain activity analysis. Unlike traditional BCI sensors that rely solely on single-electrode signal collection, sensing systems constructed with carbon nanomaterials leverage their excellent biocompatibility and electrical properties to achieve stable EEG signal acquisition while incorporating innovative structural designs to extract key characteristic parameters from complex brainwave signals. This enables more precise capture and interpretation of brain activity states and neural functional changes.

Francesca et al. developed epitaxial graphene (EG)-based sensors that significantly reduce skin contact impedance while exhibiting exceptional durability [50], as shown in Figure 6a–f. Even when exposed to high-salinity environments simulating medical applications, these sensors maintain reliable performance during extended periods of repeated use, enabling the acquisition of highly sensitive and stable EEG signals. This technology demonstrates significant implications for medical rehabilitation and related fields.

Current researches on carbon-based brain–machine interface sensors mainly focus on utilizing the excellent biocompatibility and electrochemical properties of materials such as graphene and carbon nanotubes to develop flexible implantable electrodes that can work stably for a long time and cause minimal damage to brain tissue. Existing technology aims to achieve multimodal acquisition of neural signals (simultaneously recording electrophysiological and chemical signals) through innovative structural designs (e.g., transparent electrodes and dynamic fiber electrodes) and improve stability and anti-interference ability in complex environments (such as nuclear magnetic resonance). Future trends aim to higher throughput integration, lower tissue damage, and perception computing integration, promoting the practical application of brain–computer interfaces in fields such as medical rehabilitation, intelligent prosthetics, and human–machine integration.

The integration of carbon-based BCI sensors and artificial intelligence will advance toward deep brain activity interpretation and multi-scenario precision applications. The next phase involves feeding neural signals collected by sensors into AI systems for brain activity analysis. On one hand, incorporating machine learning models enhances the understanding and processing capabilities for complex EEG signals, enabling more accurate analysis of brain states and neural intent decoding. On the other hand, integrating low-power algorithms with portable devices holds promise for real-time, continuous brain activity monitoring and analysis, propelling carbon-based BCI sensing systems toward greater application depth.

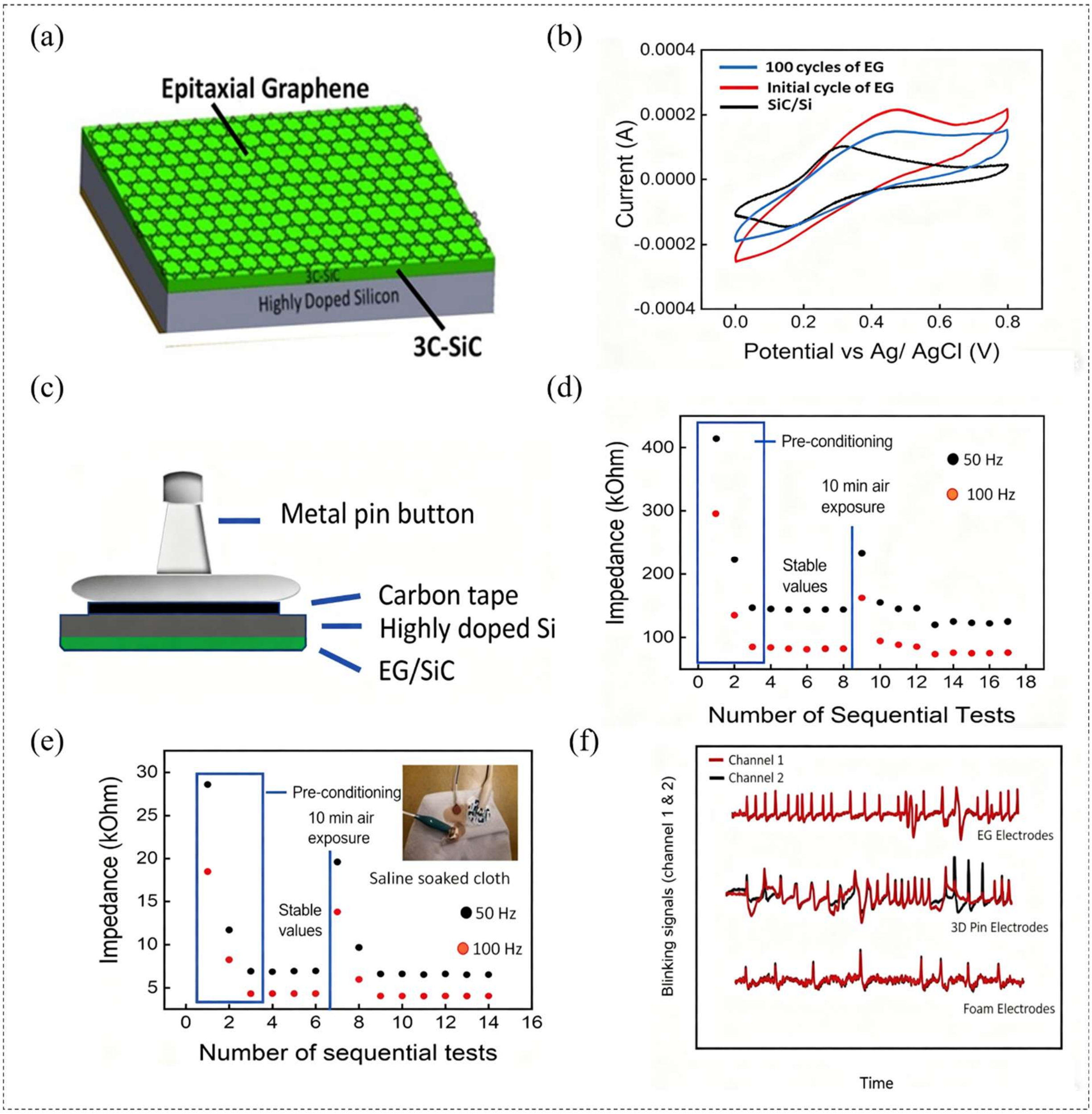

Figure 6. (a) Schematic of the epitaxial graphene electrodes, grown on cubic SiC on highly doped silicon. (b) Cyclic voltammograms of EG and SiC on highly doped silicon in 0.1 M NaCl electrolyte at a potential limit of 0.8 V versus Ag/AgCl in a three-electrode system. (c) Schematic showing the approach for the EG electrode mounting for its use as a sensor. (d) Contact impedance on-skin for EG-based sensors presented versus the number of sequential tests performed at 50 and 100 Hz without breaking the contact with skin and repeating after a 10 min interval of air exposure of the sensor. (e) Contact impedance on a saline-soaked cloth for the EG-based sensors presented versus the number of sequential tests performed at 50 and 100 Hz without breaking the contact with skin, and resumed measurements after a 10 min interruption of the sensor contact with the skin; three-electrodes EIS measurement setup onto a 0.01 M phosphate buffered saline solution-soaked cloth. (f) Comparison of signals collected with two channels on the forehead using epitaxial graphene, commercial pins, and commercial foam sensors (Reproduced from Ref. [50] with permission).

2.6. Development trends

To enhance the capabilities of artificial intelligence–carbon-based sensors in collecting data and processing information within more complex application environments, the following two development trends are proposed: multi-modal physical quantity perception systems and integrated sensing-computing analytical systems.

Single-modal sensors often exhibit significant limitations in complex environments. For instance, optical sensors are susceptible to illumination and occlusion, acoustic sensors face interference from ambient noise, and temperature sensors struggle to capture morphological changes of objects. Such unidimensional perception biases can lead to incomplete information acquisition, weak anti-interference capabilities, and even misjudgments in critical scenarios. Consequently, there is a need to advance sensors from single physical-quantity detection toward multidimensional information fusion and analysis. Carbon nanomaterial-based multi-modal sensing systems not only leverage the inherent diversified physical properties of materials to achieve synchronous detection of multiple physical quantities (e.g., temperature, pressure, light intensity) but also require subsequent decoupling of the detected data by physical quantity. AI algorithms, with their powerful pattern recognition and adaptive learning capabilities, have become the core engine for this decoupling: they automatically analyze correlation patterns in multi-modal data, precisely separate individual physical quantities from noise, and ultimately enable the leap from multi-source data to accurate cognition, ensuring stable and reliable judgments by intelligent systems in complex scenarios.

Multimodal systems have excellent multiparameter perception capabilities, as well as high sensitivity, fast response, and excellent stability and durability. By integrating convolutional neural networks and multimodal supervised learning algorithms, the system can intelligently recognize and classify complex sensing signals. High precision and strong adaptability have been demonstrated in complex practical application scenarios, supporting functions such as state monitoring and intelligent interaction. Two related research results are as follows:

Li et al. developed a carbon nanotube–based composite aerogel sensor exhibiting ultralow thermal conductivity and exceptional electrical/thermoelectric properties, enabling dual temperature-pressure responsiveness [51]. As shown in Figure 7a–d, it achieves a minimum detectable temperature change of 0.03 K, a pressure detection limit of 0.3 Pa, high sensitivity (33.5 $\mu V \cdot K^{-1}$ for temperature; $-45.2\% \cdot kPa^{-1}$ for pressure), and robust stability. The system is based on the 1D CNN modality to achieve differential extraction of signal features: low-frequency features in the "gradual rise and fall" of the self-powered mode voltage timing signal are extracted through a one-dimensional convolutional layer, and then the key features are retained through a max pooling layer to remove high-frequency noise and obtain temperature signals. By using smaller convolution kernels and more neurons, the high-frequency features of "pulse-like fluctuations" in the resistance timing signal under input bias mode can be extracted to obtain pressure signals. In subsequent research, the system was integrated with 3D CNN and achieved 100% recognition accuracy in classifying the electrical signals generated by finger trajectories. This showcases the precision achieved through the integration of multimodal perception and artificial intelligence technology in complex detection scenarios, offering strong technical support for condition monitoring and intelligent interaction.

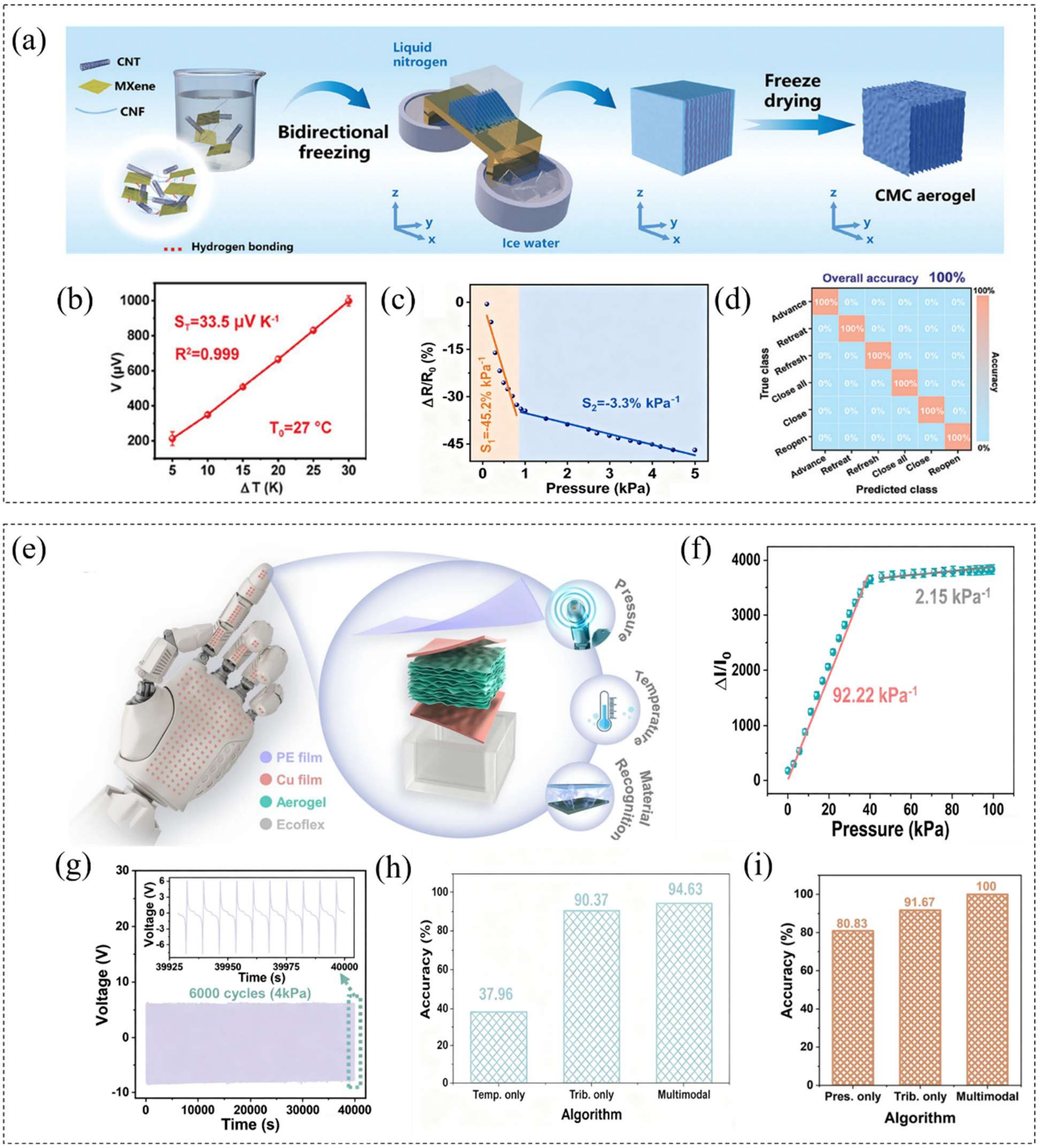

Figure 7. (a) Schematic diagram of the preparation process of carboxymethyl cellulose (CMC) aerogel. (b) Output voltage generated by the CMC sensor as a function of the temperature gradient. (c) Electrical resistance changes of the CMC sensor. (d) Recognition results post-training, achieving 100% accuracy (Reproduced from Ref. [51] with permission). (e) Schematic diagram of the sensing system. (f) Sensitivity of pressure sensing and normalized current response. (g) Robustness testing regarding the triboelectric sensing performance of the sensor. (h) Histogram of accuracy comparison between an unimodal approach and a multimodal approach for common foods. (i) Histogram of Martian terrain accuracy comparison between an unimodal approach and a multimodal approach (Reproduced from Ref. [52] with permission).

Zhao et al. developed a novel ultra-lightweight multifunctional tactile nanolayer carbon aerogel sensor capable of pressure, temperature, material discrimination, and 3D spatial mapping [52]. Integrated with a multimodal supervised learning algorithm for object recognition, it detects human-perceptible pressure (0.04–100 kPa) and temperature (21.5–66.2 °C) with a 11 ms response time, achieving 92.22 kPa^{-1} pressure sensitivity and triboelectric durability exceeding 6000 cycles, as shown in Figure 7e–i. The algorithm has designed a "dual-branch CNN feature extraction module" to address the differences between pressure/temperature and frictional electricity. The electrical signal measured by the input sensor is used to extract time-domain features through a 1D convolutional layer, and then down sampled through a max pooling layer to preserve key features and eliminate noise, which can capture the relevant features of mechanical deformation and thermoelectric effects. Using smaller convolution kernels and more neurons, it focuses on extracting the peak direction and waveform period of the signal and frictional electrical signals. The designed algorithm demonstrates versatility, being adaptable to diverse application scenarios. For instance, it achieved 94.63% recognition accuracy for common foods in kitchen settings, while achieving a 100% recognition rate on simulated Martian terrain.

In the field of integrated sensing-computing, technological innovation is driving breakthroughs from separated data processing toward integrated real-time responses. Unlike traditional sensor systems with segregated sensing and computing units, carbon-based integrated sensing-computing systems merge sensing and computational functions to perform real-time processing and analysis during data acquisition. Through unified design, they eliminate data transmission between functional units, thereby drastically improving system response speed and significantly reducing power consumption.

The integrated sensing-computing system performs excellently in core sensing capabilities, breaking the separation mode of perception and processing through programming and integration technology, and forming an efficient collaborative sensing system. It has demonstrated practical value in the fields of intelligent touch and human–computer interaction. A related research result is as follows: Liao et al. have proposed a CNTs-based location-pressure intelligent (LPI) tactile sensor [53]. By integrating perception, computation, and logic functions, it enables highly efficient and precise action-intention interaction. The LPI tactile sensor demonstrates excellent resolution in both location and pressure detection, as shown in Figure 8. Furthermore, through programming and integration techniques, it achieves logical coordination between different touch actions. This logical coordination mechanism allows for direct interaction with targets, facilitating precise intervention in tactile intentions. The sensing system fully demonstrates the significant advantages of integrated sensing-computing design for efficient interaction, providing technical support for intelligent touch and human–computer interaction.

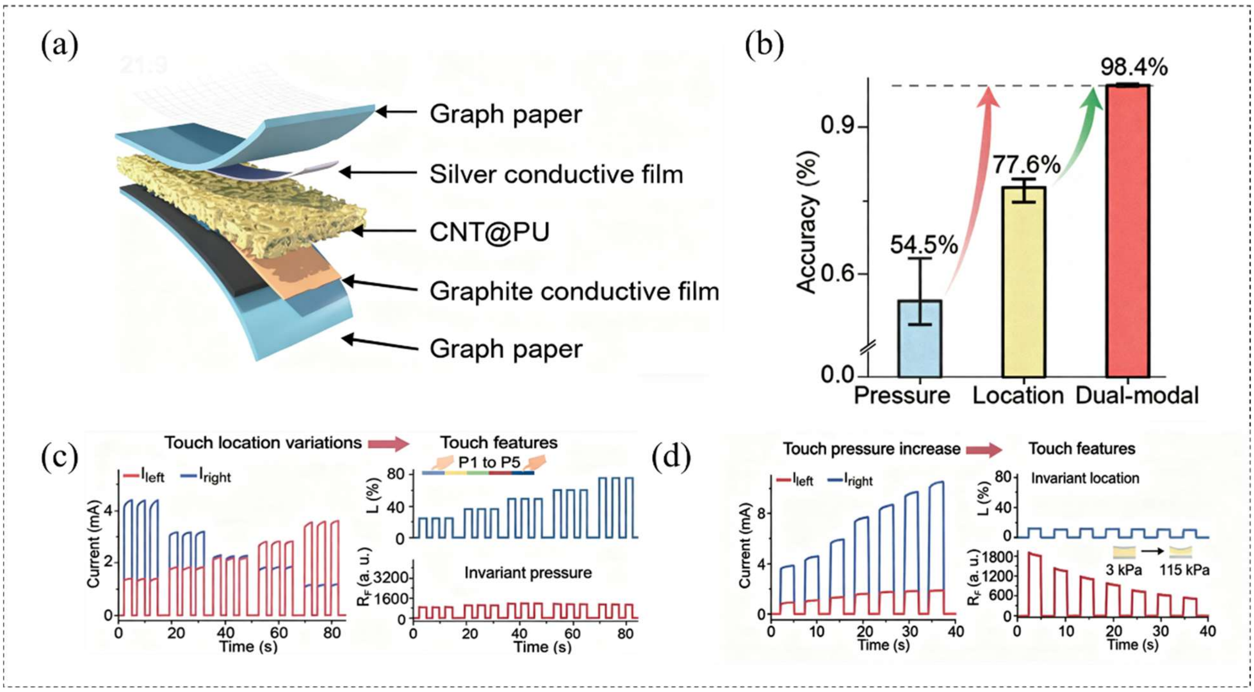

Figure 8. (a) Schematic diagram of the LPI tactile sensor. (b) Recognition accuracy based on different touch feature datasets. (c) Response current of the LPI tactile sensor at different positions and decoded contact position L and pressure radio frequency (RF) parameters. (d) Response current of the LPI tactile sensor under different pressures and decoded contact position L and pressure RF parameters (Reproduced from Ref. [53] with permission).

Multi-modal sensing systems and integrated sensing-computing systems represent critical development trends. Multi-modal sensing systems leverage carbon nanomaterials to achieve synchronous multi-physical-quantity detection, combined with AI algorithms for data decoupling, demonstrating outstanding detection and recognition capabilities. Integrated sensing-computing systems merge the sensing and computational functions of carbon-based materials, eliminate data transmission bottlenecks, and exhibit significant advantages in response speed, power efficiency, and resolution, providing robust technical support for related fields. The development and applications are systematically summarized in Table 2. The ANN in the table is an abbreviation for artificial neural network. The CNN in the table is an abbreviation for convolutional neural network.

Table 2. Carbon-based sensor development trend and applications.

Category	Sensor type	Applications	AI model	Excellent performance
Multimodal information acquisition	Pressure/temperature sensor	Housekeeping robots [54]	ANN	Ultrafast slip sensing
	Temperature/chemical composition sensor	Real-time environmental monitoring [55]	ANN	High sensitivity
	Pressure/temperature sensor	Intelligent object recognition [52]	CNN	Wide temperature/pressure detection range
	Pressure/temperature sensor	Human-machine interaction [51]	CNN	High sensitivity and stability
Integrated sensing-computing	Pressure sensor	Intelligent touch control [53]	CNN	Excellent resolution
	Optical sensor	Dynamic visual recognition [48]	CNN	Synaptic plasticity
	Optical sensor	Image recognition [56]	ANN	Broadband photo perception

2.7. Perspective and challenges

Low-dimensional carbon nanomaterial sensors have excellent intrinsic performance, and their combination with artificial intelligence enables a transformation from simple data collection to complex information perception and processing. The multimodal sensing system improves the integrity of perception through information fusion; the integrated architecture of sensing and computing provides direction for achieving real-time, low-power intelligent sensing.

Although low-dimensional carbon nanomaterial sensors integrated with artificial intelligence have shown great potential for application, their further development still faces key challenges.

The inherent characteristics of carbon nanomaterials still present shortcomings. First, there is insufficient stability and environmental adaptability. Some carbon nanomaterial sensors exhibit significant performance degradation under complex operating conditions, such as high-humidity environments. Second, the accuracy of performance tuning is limited. Although sensor performance can be optimized through chemical doping and microstructure design (such as micro pyramid structures), it is difficult to synergistically regulate the coupling between physical quantities, and further exploration is needed to investigate the structural performance relationship between material structure and multiple physical quantity responses.

At present, there is still room for improvement in the integration of artificial intelligence and carbon nanomaterial sensors: data dependency is strong, and most algorithms (such as supervised learning) require large-scale annotated datasets for training. However, the dynamic response signal of carbon nanomaterial sensors presents large individual differences and complex noise, and the cost of obtaining high-quality label data is high.

It is believed that with the continuous iteration of technology, the above scientific problems can be solved, the performance of carbon-based sensors can be further improved, and they can be widely applied in the era of intelligence.

3. Conclusions

This article systematically investigates the integration of carbon-based sensor technology and artificial intelligence, outlining the developmental trends underpinning next-generation intelligent sensing platforms. By leveraging the exceptional electron mobility, superior thermal conductivity, and mechanical strength of carbon nanomaterials, combined with AI feature extraction and learning capabilities, carbon-based sensors are rapidly evolving beyond mere signal acquisition into multifunctional, integrated sensing and computing modules.

The integration of carbon nanostructures and AI has enabled high-resolution sensing with robust adaptability across diverse application environments—spanning mechanical, acoustic, thermal, optical, and brain–computer interface domains. These advancements extend from contactless health diagnostics and voice-interactive wearables to cognitive state monitoring and neural interface systems. Such intelligent sensors not only enhance data fidelity but also introduce functions like behavioral prediction, emotion recognition, and real-time feedback control, offering new avenues for research in high-performance biomedical systems, robotics, and brain–computer communication technologies.

Carbon nanomaterials have inherent defects in stability and environmental adaptability, and the current integration of artificial intelligence and carbon-based sensors still faces key challenges, such as strong data dependence and difficulty in balancing real-time performance and power consumption. Improving carbon-based sensors and artificial intelligence systems in these areas is a very important research direction for the future. It is believed that with the continuous optimization of carbon-based sensor plans and in-depth research on artificial intelligence algorithms, the vigorous development of a future intelligent society can be promoted.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Yi Zhang: writing—original draft; Lu-Yu Zhao: methodology; Yu-Tao Li: methodology & supervision; Ye-Liang Wang: supervision.

Conflict of interest

The authors declare no conflict of interest.

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