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Wearable Internet of Things enabled precision livestock farming in smart farms: A review of technical solutions for precise perception, biocompatibility, and sustainability monitoring

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ABSTRACT

Precision, sustainability and intelligence are the development trend of livestock farming in the future. Precision livestock farming (PLF) is a key step to achieve the sustainable development of smart farms, but it is still in the initial stage and has broad prospects. In order to realize precise livestock production, it is necessary to speed up the popularization of intelligent technologies such as environmental control, disease early warning, precise feeding and remote diagnosis. By analyzing the background and technical features of wearable Internet of Things (W-IoT), this paper puts forward a new scheme of applying W-IoT to PLF. Through the detailed survey of the related research on W-IoT and PLF, we believe that precise perception of information, biocompatibility of wearable devices, and sustainability monitoring of wearable systems are necessary contents. However, most wearable technologies that can generate precise, dynamic and sustainable signals are only applicable to humans, and rarely modified or tested specifically for farm animals. At present, these innovative technologies are gradually promoted to livestock farming, which are expected to become one of the most effective solutions for PLF in smart farms. In addition, this paper also discusses the benefits, challenges and prospects of the W-IoT in farm animals.

1. Introduction

In recent years, with the gradual withdrawal of the family-style farming model, the livestock farming has gradually developed towards the trend of intensive, large-scale and intelligent in China (Zhang et al., 2019a; Tan et al., 2020). Supported by "Internet +", it has promoted the integration and innovation of the new generation of information technology, modern manufacturing and producer services, represented by cloud computing, Internet of things and big data. Using modern information technology to solve the shortcomings and problems of traditional livestock farming, explore the development mode of modernization, and stimulate the internal growth power of livestock farming is of great significance to promote and realize the stable and sustainable development. Therefore, the livestock farming is undergoing a great change, the traditional farming management experience is no longer feasible, and will gradually withdraw from the historical stage. In the future, the livestock farming will usher in the new trend of precise and intelligent management.

As defined in the literatures (Tullo et al., 2018; Lovarelli et al., 2020; García et al., 2020), Precision livestock farming (PLF) is a management mechanism of production system based on process engineering principle. This management mechanism can continuously monitor the process or results, and generate the mathematical models for predicting the inputs, and the inputs can be controlled in turn for the expected results. Therefore, precision livestock production can improve the utilization efficiency of the resources and reduce the breeding cost. At present, PLF is still in the initial stage, but it is undeniable that it has broad prospects. In order to realize precision livestock production, the popularization of

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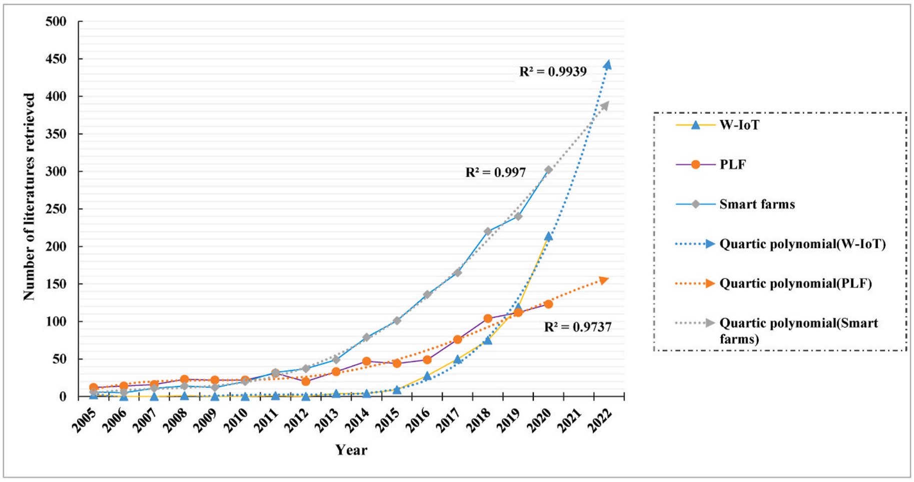

Fig. 1. The results of literature retrieval based on the identified subject areas.

intelligent technology must be accelerated in the future (García et al., 2020; Maia et al., 2020). The main contents are as follows (Gattani et al., 2019; Costantini et al., 2020; Torky et al., 2020): speed up the integration of intelligent sensing, wireless sensing, automatic control, remote monitoring, accelerate the application of intelligent technologies such as environmental control, precision feeding, epidemic prevention and control, remote diagnosis, automatic waste recovery and treatment, quality traceability in large-scale livestock and poultry breeding bases, and speed up the realization of modern management that is visible and traceable throughout the breeding process.

References (Neethirajan et al., 2017; Gattani et al., 2019) indicate that the biosensor technology can efficiently monitor and record the physiology, movement, behavior and living environment of farm animals in real time, which plays an important role in the management of precise feeding, estrus monitoring, epidemic disease warning, precise milking, etc. In addition, timely feedback can be made through the Internet platform, and big data can be used to tell managers and decision makers about the state of each livestock and poultry in the ranch every day, so as to make corresponding decisions in time. But the integration of wearable devices, sensors and communication technology is the key scientific issues of physiological monitoring, and is also the premise of real-time monitoring, precise recording and control (Nadimi et al., 2008; Kim et al., 2017; Cui et al., 2019). Now with the help of Internet of things technology, sensors and wireless communication technology can be embedded into wearable devices, which can be quickly arranged, convenient to adjust, and has good maintainability and expansibility (Zhang et al., 2019a; Cui et al., 2019). Therefore, the advantages of wearable Internet of Things (W-IoT) technology are that it can collect massive data at almost any time, places and environmental conditions, which is easy to analyze and evaluate the status of the objects monitored, so it can be widely used in livestock farming, etc.

Currently, the monitoring of physiological indicators on animals, especially the research of stress response, mostly focus on the static detection of biochemical indicators (Kadim et al., 2014; Terré et al., 2019). However, the problem is that the stress signal of animal body changes smoothly, with poor continuity, and traditional equipment has high power consumption, which makes it impossible to achieve real-time and continuous monitoring. As bioinformatics sensors can quantify a variety of physiological and behavioral responses of livestock and poultry, providing significant benefits and applications in health monitoring, reproduction, and feeding. So, W-IoT technology is expected to become one of the most effective and feasible technical solutions for animal health supervision. Although many sensors for animal health management are in different stages of commercialization, some technologies that can produce accurate health and disease diagnosis are only applicable to humans, so there is a gap in this field for farm animals (Neethirajan et al., 2017). Now, these innovative technologies are being considered for the future development of livestock farming, such as sound analysis (Zhang et al., 2019a), behavior analysis (Noble et al., 2017; Achour et al., 2019), environmental perception (Pereira et al., 2020), image processing (Mcmanus et al., 2016), biological sensing (Neethirajan et al., 2017), etc.

This paper aims to summarize the application vision of W-IoT in precision livestock production and management of smart farms in the future. Comprehensive technical elaboration from three aspects of precision, biocompatibility, and sustainability can make up for the gap of W-IoT in farm animal farming and management. We think this research has great research significance and application value. Section 1 introduces the development status and technical elements of PLF and W-IoT. Section 2 explains the research methodology, and three aspects (precise perception of information, biocompatibility of wearable devices, and sustainability monitoring of wearable systems) of W-IoT used for PLF are proposed. Section 3 analyzes the advanced sensors and data fusion which can be applied to the monitoring of behavior, environment, and physiology of farm animals. Section 4 describes the biocompatibility of wearable devices. Section 5 describes the sustainability monitoring of wearable systems. Section 6 discusses the benefits, challenges and prospects of the W-IoT in farm animals. Finally, the conclusion is given in Section 7.

2. Research methodology

2.1. Literature retrieval strategy

This paper puts forward a technical scheme of applying W-IoT to PLF in smart farms. To achieve research objectives and help to solve specific problems in actual production, technical reviews are mainly conducted on precise perception, biocompatibility, and sustainability monitoring of W-IoT. However, most of the current literatures on wearable technology focus on human applications, and some of them are applied to family pets, with few modifications or tests for farm animals. However, it is undeniable that W-IoT has great application potential in animal welfare, health management and food quality traceability. Literature review includes the selection of relevant search terms and literature resources. For the purpose and scope of research, publications in subject areas are preferred from influential databases and international journals. To effectively classify and use the existing literatures, the following criteria are adopted (Stojkoska et al., 2017; Feng et al., 2020; Yanes et al., 2020):

Table 1
On the comparison of recent literature related to the research topics of this review.

References	Research topics	Technology integration	Research contents	Applied objects	Sustainability	Research levels
Astill et al. (2020)	Smart poultry management	Sensors Big data IoT	Environmental monitoring Precision feeding Welfare monitoring Virus detection	Poultry	Yes	Application Integration/ Fundamental research
Garcia et al. (2020)	PLF	Machine learning Big data	Animal health Animal behavior Animal monitoring	Livestock	No	Application Integration
Godyń et al. (2019)	PLF	Infrared thermography Thermistors	Peripheral temperature measurement Core temperature measurement	Cattle	No	Application Integration
Hendriks et al. (2020)	Animal ethology	Wearable accelerometers	Behavior monitoring Behavior analysis	Dairy cows	No	Application Integration
Legner et al. (2019)	Health management	Wearable devices Sweat sensors	Sweat sensing Power generation Data management	Human body	Yes	Application Integration/ Fundamental research
Lovarelli et al. (2020)	PLF	Wearable devices Sensors	Economy with PLF Environment with PLF Social sustainability with PLF	Dairy cattle	Yes	Application Integration
Nasirahmadi et al. (2017)	Animal ethology	Machine vision 3D imaging systems	Feeding and drinking behavior Lying behavior Locomotion and lameness behavior Aggressive behavior	Cattle and pigs	No	Application Integration
Neethirajan et al. (2017)	Health management	Biosensors Decision support system	Behavior monitoring Breath analysis Sweat sensing Glucose monitoring	Livestock	No	Application Integration/ Fundamental research
Pons et al. (2017)	Animal ethology	Machine learning Tracking system	Behavior monitoring Behavior analysis	Animals	No	Application Integration
Tullo et al. (2018)	PLF/Sustainability	Precision feeding Lameness detection Mastitis detection	Environmental effects of livestock farming Strategies to mitigate environmental risks	Livestock	Yes	Fundamental research
Zhang et al. (2019b)	Smart agriculture	Infrared temperature measurement technology Infrared image processing technology	Body temperature measurement of pig	Pig	No	Fundamental research
This review	PLF/Smart farms	W-IoT Advanced sensors Flexible electronics Self-powered technology	Precise perception of information Biocompatibility of wearable devices Sustainability monitoring of wearable systems	Livestock	Yes	Application Integration/ Fundamental research

1) Search the literatures through the international famous database.
2) The time distribution and subject types of publications are in line with the future development trend.
3) Give priority to the literatures closely related to this research.
4) If two or more papers have the same topic, choose the latest published paper.

In order to fully understand the research hotspots and application trends, this research conducts a strict search mainly based on ScienceDirect (https://www.sciencedirect.com/), and uses Web of Science (https://apps.webofknowledge.com/WOS_GeneralSearch_input.do?product=WOS&SID=7FxEJY3RINSHIF5Gg4e&search_mode=GeneralSearch) and CNKI (https://www.cnki.net/) for auxiliary search. These databases contain a large number of peer-reviewed journals around the world. The key words of the search are "wearable Internet of things", "precision livestock farming" and "smart farms", the subject areas of the search are "Engineering", "energy", "materials", "environment", "Electronics", "biomedicine", etc., and the retrieved journals include "Science", "Nano Energy", "Journal of Cleaner Production", "Computers and Electronics in Agriculture", "Science of The Total Environment", "Energy", "Agriculture, Ecosystems & Environment", etc. It is found that the high-quality research literatures related to this study began to appear at the beginning of this century, so the time cycle of literature retrieval is from 2005 to 2020. The results of relevant publications from 2005 to 2020 are shown in Fig. 1. The rising trend of the number of publications shows that the research interest in "PLF", "smart farms" and W-IoT" has increased sharply, with an average growth rate of 18%, 23% and 63% respectively during 2017–2020. According to the prediction results of quartic polynomial fitting, the research trends of the three topics will continue to reach new heights, especially the research related to the W-IoT.

Table 1 shows the published review papers related to the research contents of this review. Literature analysis shows that the research and application of W-IoT in livestock farming have appeared, such as wearable ear tag, wearable accelerometer, visual tracking, etc. Although the research directions of W-IoT, PLF and smart farms are more popular recently, there is no clear definition and comprehensive technology review and integration for the future research and application of W-IoT in PLF and smart farms, and W-IoT is more about the research and application of human beings, and rarely carries out professional testing for animals, especially farm animals. In addition, the traditional technical solutions have few functions, and the ability to improve breeding efficiency, save energy and promote sustainable development is limited, which cannot achieve the goal of precision farming in smart farms. To express how the W-IoT is applied to livestock farming in the future, this paper makes a clear definition of it, and carries out literature review and

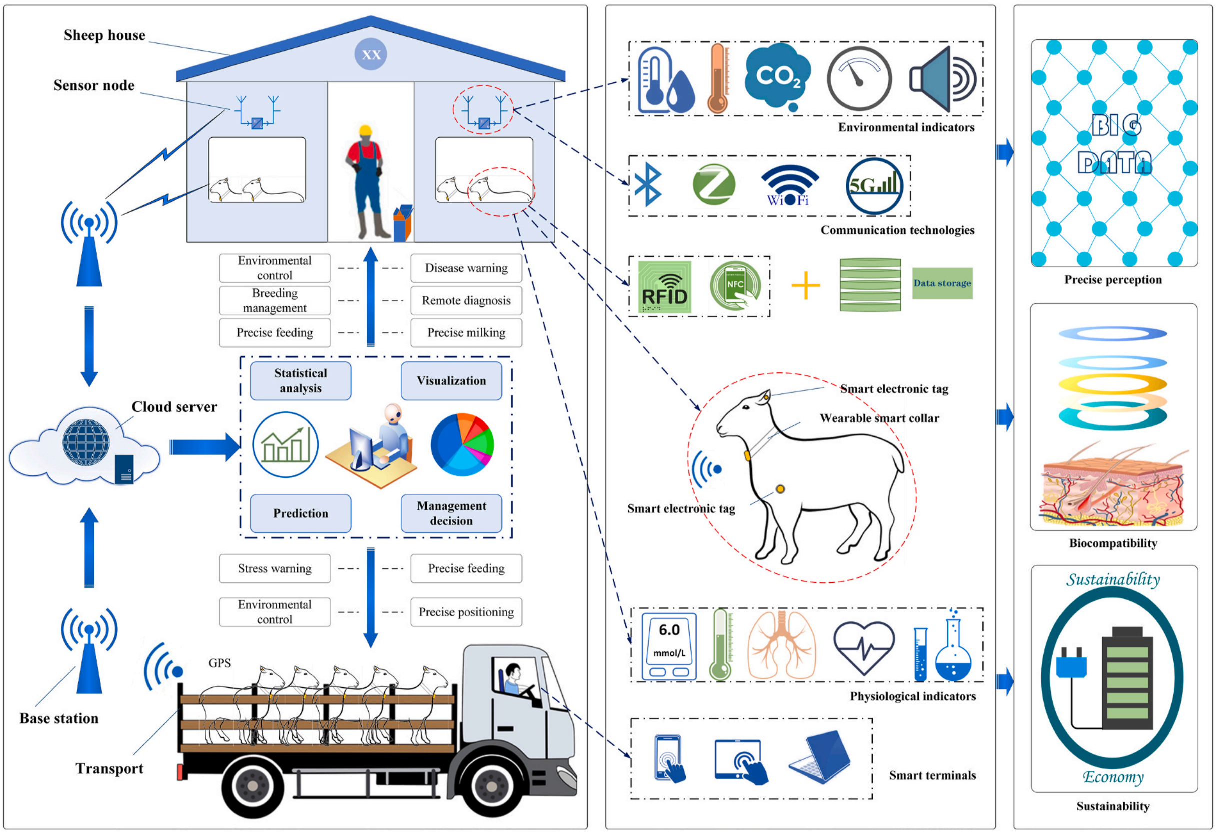

Fig. 2. Schematic diagram of W-IoT for PLF in smart farms.

case analysis from the accuracy of data acquisition, biocompatibility and sustainability monitoring, aiming to put forward practical technical solutions.

2.2. Research analysis framework

With the increasing maturity of sensors, chips, wireless communication, people have more stringent requirements for wearable technology. Wearable devices, smart phones and surrounding environment devices are equipped with various sensors for activity detection and monitoring, such as electrocardiogram (ECG) sensors, accelerometers, gyroscopes, magnetometers, and wearable cameras have been widely used in sports and fitness, health monitoring, disease diagnosis, location tracking, etc. In medical diagnosis, the personalized instant diagnosis equipment assisted by smart phones is the research trend (Purohit et al., 2020). By integrating smart phones with biosensors to develop this kind of personalized instant diagnosis device can make it portable and easy to wear, and reduce manufacturing costs, which may revolutionize the diagnosis industry. In animal management (Neethirajan et al., 2017; Zhang et al., 2019a; Cui et al., 2019), wearable biosensors as an application of animal health monitoring are widely accepted and recognized, because animal health is a global problem that needs to be solved with new technologies, such as the application of biosensors in animal health management. PLF is the development trend, which needs to integrate all available sensors and create an efficient online monitoring system to monitor animal health in real time and without delay. However, Neethirajan et al. (2017) pointed out that some technologies that can produce accurate health status and disease diagnosis are only applicable to humans, and are rarely modified or tested for animal models. In the future, these innovative technologies are gradually being extended to the livestock farming industry and are expected to become the most effective solutions for PLF.

Although the research on wearable technology is becoming increasingly hot, and the application fields are wide. However, there is a lack of comprehensive analysis and research scheme in PLF and smart farms from W-IoT. In the field of animal husbandry, considering cost issues, most of the research and applications are relatively scattered and low-tech, such as ear tags, pedometers, etc., which are increasingly unable to meet animal welfare and human quality requirements for livestock products. Moreover, the current research and application of wearable technology are still largely focused on humans, and there are few professional tests on animals, especially the precise and intelligent management of large-scale farm animals. In short, by analyzing the background and technical features of the W-IoT, this paper proposes to apply W-IoT to the precise and sustainable monitoring of livestock farming, to promote the new trend of informatization, precision, and intelligent management. The schematic diagram of W-IoT for precision livestock production in smart farms is shown in Fig. 2.

3. Precise perception of information based on W-IoT

3.1. Advanced sensors

Physiological sensors need to be integrated on wearable devices or substrates to monitor various indicators and external stimuli. Now with the development of all organic biocompatibility technology, wearable systems for in vivo monitoring become possible (Matzeu et al., 2015). However, the development of wearable sensors faces many challenges (Salim and Lim, 2019), including the selection of appropriate substrates, manufacturing processes and biocompatible materials, as well as how to ensure the washability of the materials, simultaneous monitoring of different analytes, sensing mechanism, signal circuit and wireless data transmission, etc. Previous studies (Mannoor et al., 2012; Matzeu et al., 2015; Legner et al., 2019; Chung et al., 2019; Singh et al., 2020) have demonstrated that the sensors used in wearable devices can be divided into biosensors, chemical sensors, and physical sensors according to the

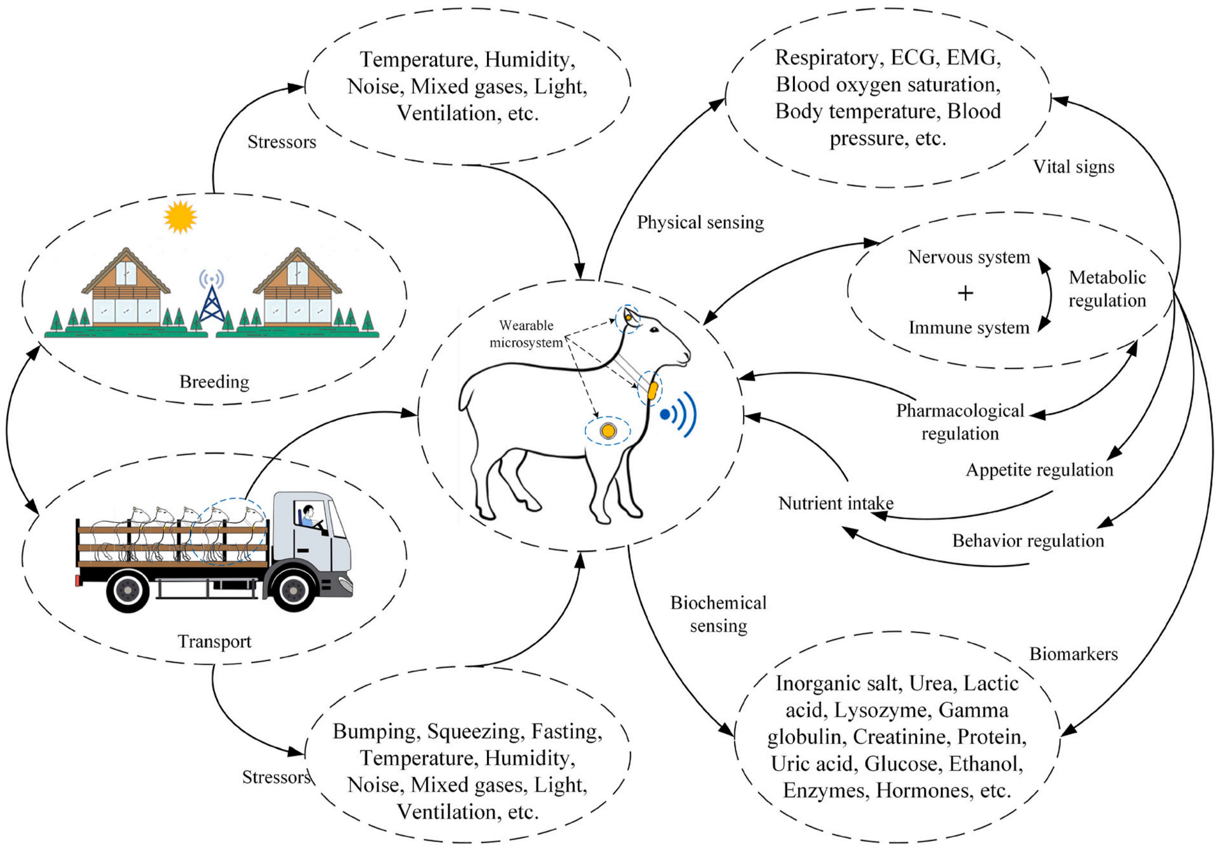

Fig. 3. Schematic diagram of information perception using wearable devices for PLF in smart farms.

working principle and can be divided into microsensors and intelligent sensors according to the integrated state. These wearable sensors are mainly used to monitor vital signs parameters (such as pulse rate, blood oxygen saturation, body temperature, respiration, etc.), behavior and movement parameters (such as gait feature, etc.) of farm animals, and can also identify various biological markers (such as glucose, lactic acid, pH, etc.) (Fig. 3).

3.1.1. *Biochemical sensors*

Wearable and flexible biochemical sensors have great potential in contact with skin and noninvasive extraction of biological fluids for real-time and continuous monitoring of physiological state of farm animals (Fig. 4a presents the schematic illustration of the skin layers with different wearable devices). In principle, the chemical sensors are miniaturized devices that can specifically and reversibly respond to a certain chemical component and can generate measurable signals proportional to the concentration of the component (Parrilla et al., 2019; Legner et al., 2019). And the biosensors use the bioactive units (such as enzyme, antibody, nucleic acid, cell, etc.) as the sensitive unit, which have high selectivity to the tested substance (Mannoor et al., 2012; Reid and Mahbub, 2020; Singh et al., 2020). Due to the close relationship between biosensors and chemical sensors, they are usually called biochemical sensors together (Campbell et al., 2018). Regardless of the sensing mechanism and manufacturing technology, compared with physical sensors, precise monitoring is the advantage of biochemical sensors (Table 2). For instance, Chu et al. (2011) developed and tested a soft contact lens biosensor for in situ monitoring of tear glucose (Fig. 4b). The result showed a good relationship between the output current and glucose concentration in a range of 0.03–5.0 mM, with a correlation coefficient of 0.999. Therefore, the contact lens biosensor is expected to provide more accurate information about the relationship between blood glucose dynamics and tear glucose. And Parrilla et al. (2019) pointed out that recent studies have shown that wearable potential ion sensors are involved in the precise detection or continuous monitoring of key biomarkers. These ions, such as sodium, potassium, calcium, magnesium, ammonium, and chloride, have relatively high concentrations in sweat, which can be used to reflect the physiological state (Fig. 4c).

Biochemical molecular recognition element and signal converter are the basic units of biochemical sensors. The former is composed of sensitive materials, such as chemical sensitive membrane composed of semiconductor materials and biological sensitive membrane formed by enzyme, microorganism, deoxyribonucleic acid (DNA), while the latter is mainly composed of electrochemical or optical detection elements, such as potential measuring electrode, piezoelectric crystal (Chu et al., 2011; Mannoor et al., 2012; Reid and Mahbub, 2020; Singh et al., 2020). For instance (Fig. 4d), Mannoor et al. (2012) demonstrated the micro-system of wireless nano sensor based on biotransferable graphene. Graphene was printed on bioabsorbable silk, and a wireless coil was formed on the contact surface, which combined pathogenic bacteria on the graphene nano sensor through self-assembled peptide to realize single-cell detection and passive wireless monitoring.

The development of high-performance sensors with high specificity, high sensitivity and short response time has always been the goal. At present, the advantages and challenges of developing biochemical sensors are clear, mainly as follows:

- The biochemical sensors have the advantages of strong specificity and high sensitivity, especially the biosensors use enzymes, antibodies, nucleic acids, etc. as biological sensitive units, and have high selectivity for the tested substance.
- Technologies such as microelectromechanical systems and nanomaterials promote the miniaturization, integration and multi-functionalities of biochemical sensors. At present, a variety of new

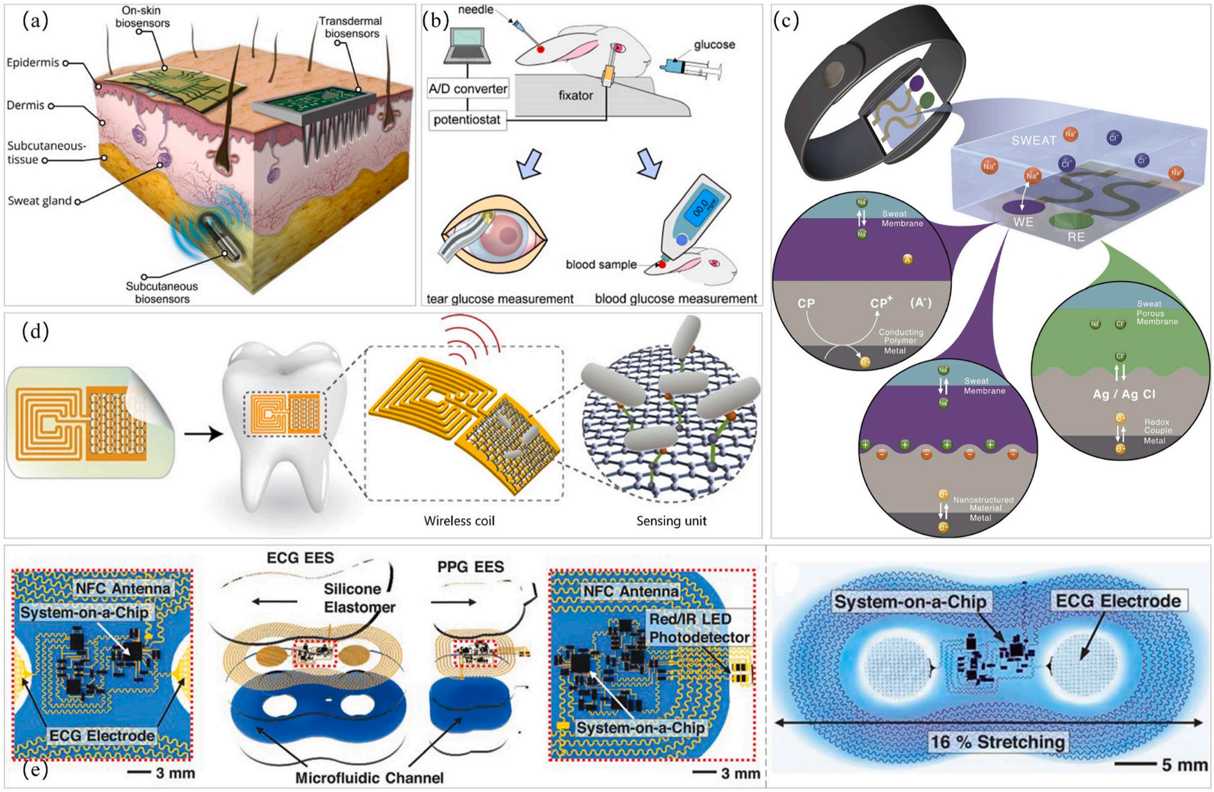

Fig. 4. The typical research cases of biological, chemical, and physical sensors. (a) Schematic illustration of the skin layers with different wearable devices (Dervisevic et al., 2020). (b) Measurement method of tear glucose concentration with the contact lens biosensor. Blood glucose level was measured by a commercially blood glucose monitoring kit, simultaneously (Chu et al., 2011). (c) Schematic illustration of wearable potentiometric ion sensor (WPIS) based on a bracelet that was modified with the working/indicator electrode (WE) and a reference electrode (RE) to provide a WPIS (Parrilla et al., 2019). (d) Biotransferrable graphene wireless nanosensor (Mannoor et al., 2012). (e) Schematic illustration of wireless, battery-free modules for recording electrocardiogram (ECG) and photoplethysmography (PPG) data and skin temperature. The ionic liquid in the microfluidic channel contains blue dye for visualization purposes (Chung et al., 2019).

Table 2
The performance and classification of potential sensors for W-IoT.

Types	Target index	Principle or detection method	Linear Range	Sensitivity or Detection limit	Repeatability
Biosensors	Glucose	Amperometry (sweat)	0–200 μM	2.35 nA μM^{-1}	Yes
	Lactate	Amperometry (sweat)	0–30 mM	220 nA mM^{-1}	Yes
	Uric acid	Amperometry (saliva)	0–1 mM	2.32 μA mM^{-1}	Yes
	Cortisol	Amperometry (sweat)	0.01–10.0 μM	2.68 μA dec^{-1}	Yes
	Urea	Potentiometric (sweat)	10–5000 μM	8 μM	–
	Alcohol	Electrochemistry (sweat)	2.17 $\times 10^{-3}$-43.4 mM	2.17 $\times 10^{-3}$ mM	–
Chemical sensors	Na^+	Potentiometry (sweat)	0.1–200 mM	46 mV dec^{-1}	Yes
	Na^+	Potentiometry (saliva)	0.0001–1 M	188 mV dec^{-1}	Yes
	K^+	Potentiometry (sweat)	0.1–100 mM	60 mV dec^{-1}	Yes
	Cl^-	Potentiometry (sweat)	10–160 mM	55.1 mV dec^{-1}	Yes
	Ca^{2+}	Potentiometry (sweat)	0.125–2 mM	32.7 mV dec^{-1}	Yes
	pH	Potentiometry (sweat)	3–8	60 mV dec^{-1}	Yes
	pH	Potentiometry (interstitial fluid)	3–8	59.63 mV pH^{-1}	Yes
Physical sensors	Body temperature	Radiant heat effect	−20–85 °C	0.1 °C	–
	Body temperature	Thermistor (DS18B20)	−55–125 °C	0.1 °C	–
	Heart rate	Photoelectric effect (PPG)	30-250 bpm	1 bpm	–

Note: The contents in the table are organized according to Campbell et al. (2018), Dervisevic et al. (2020), Ferreira et al. (2019), and Zhang et al. (2019a).

types of biochemical microsystems with chip-based structure and system integration as the ultimate goal have emerged, including microarray gene chips and microfluidic biochips. Meanwhile, intelligent and dexterous biochemical sensing systems with the functions of information detection, signal processing, information memory, logical thinking and judgment began to appear.

- However, biochemical sensors still have major problems to be solved, especially in the production of large-scale farm animals. On the one hand, as its sensitive materials are enzymes, antibodies, and other biomarkers, which are easy to inactivate and have strict requirements on the environment, its monitoring sustainability is poor, and its application scenarios are limited. On the other hand, as the signals generated by biochemical reactions are extremely weak and unstable, it is difficult to capture these weak signals and form stable and effective data. In addition, the primary goal of farm animal breeding is to pursue economic benefits, and reducing the cost is another important problem for the application of biochemical sensors in animal husbandry.

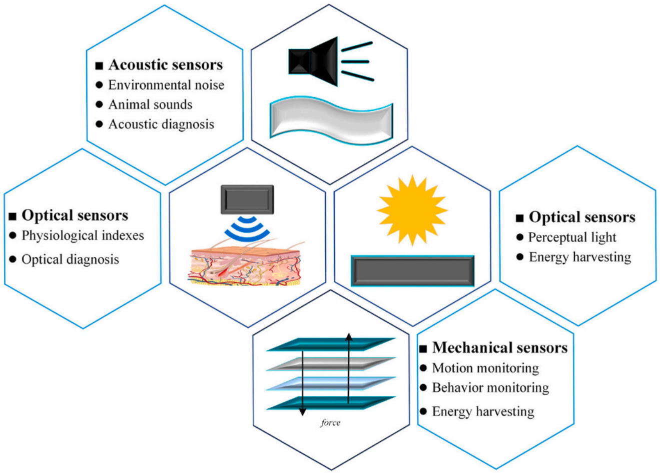

Fig. 5. The application range of physical sensors in farm animal conditions.

3.1.2. Physical sensors

Currently, physical sensors are the main components to realize the wearable continuous monitoring of vital signs on active farm animals, which can transform the measured physical quantity into the signal form that can be processed easily (Kranjec et al., 2014; Nasirahmadi et al., 2017; Benson et al., 2018; Chung et al., 2019; Nozariasbmarz et al., 2020; Pessoa et al., 2021). For instance (Fig. 4e), Chung et al. (2019) developed a wireless, passive, ultra-thin and soft vital signs monitoring system. The system used a pair of binomial ultra-thin and low modulus measurement modules, which can touch skin gently and noninvasively. The heart rate, heart rate variability, blood oxygen saturation and systolic blood pressure can be extracted by NFC communication protocol. Compared with the traditional vital signs monitoring system, it has the advantages of low energy consumption and portability. In the future, the microsystem has important reference significance in the monitoring of active animals. Fig. 5 shows the application range of physical sensors in farm animal conditions.

Physical sensors are currently the most mature and effective precision sensing tools. The specific solutions of physical sensors are as follows:

Solution 1: For the wearable monitoring of heart rate, oxygen saturation, blood pressure, and respiration, photoplethysmography (PPG) is a very convenient and efficient method (Kranjec et al., 2014). In PPG technology, the main factors that affect the detection light intensity or spectrum are blood volume, the movement of blood vessel wall, the features of tissue and the state of red blood cells. PPG can quickly analyze heart rate variability without ECG, and almost all the detection can be non-destructive. However, PPG signal is easily affected by motion artifacts, which will affect the accuracy of cardiac activity detection, which is the main disadvantage of it. Although PPG is worthy of recommendation for active farm animals, there are other methods for the research of wearable continuous monitoring, such as ultrasound and voice analysis in respiratory function diagnosis (Tong and Sataloff, 2020; Pessoa et al., 2021).

Solution 2: For the wearable monitoring of body temperature, it can be divided into the detection of skin temperature and core temperature (Taylor et al., 2014; Zhang et al., 2019b). As described by Godyń et al. (2019), in physiological parameters, body temperature and its fluctuation are key indicators of animal health and well-being. This study described the use of a thermal imaging scanner to assess the body surface temperature on the left side of a cow's body at 9 °C. The average temperature of this part of the body is 23.9 °C. The highest temperature occurred in the eyes and breast areas. In addition, the temperature of the cows recorded by infrared cameras showed that the skin temperature of the eyes (36.98 °C) was higher than the skin temperature of the shoulders (34.91 °C), and the average skin surface temperature behind the ears was 35.60 °C. Vulvar temperature was also measured with a vaginal recorder, with an average of 37.22 °C. Maybe the measurement process of body surface temperature seems very easier than core temperature, but it also has a complex mechanism. Body surface temperature is determined by many factors, such as local blood flow, heat conduction of lower tissue, heat dissipation of epidermis, and environment condition. At present, thermistor, thermocouple sensor and infrared temperature sensor can be embedded in wearable devices to accurately sense the skin temperature, but at the same time, the layout and location of the sensor should be paid attention to (Zhang et al., 2019a).

Solution 3: For the wearable monitoring of behavior and movement, the features are also feasible schemes for precise animal management, such as prediction of estrus behavior, fighting behavior and calling behavior (Nasirahmadi et al., 2017; Zhang et al., 2019a; Hendriks et al., 2020). Here, accelerometer, pressure sensor, displacement sensor, and vision sensor can be used for qualitative or quantitative analysis. For instance, Hendriks et al. (2020) proposed that wearable accelerometers provide a new opportunity for animal ethology through quantitative measurement of cow behavior (such as lying time and times). Quantitative measurement of behavior can help producers predict, diagnose, and manage diseases or injuries of farm cows, and allow producers to monitor the comfort and estrous behavior of cows. Animal behavior can be expressed in a variety of forms (fighting, barking, getting up and lying, watching, etc.), each of which reflects the animal's comfort, health status, hunger, etc. behavior research can be regarded as one of the potential development trends of precision breeding in smart farms in the future, and its obvious advantages are non-invasive, low cost and easy implementation.

3.1.3. Microsensors

Small size, light weight, and biocompatibility are the basic requirements of wearable devices to avoid introducing new stressors, thereby reducing the impact on farm animals. The existing literatures have shown that the microsensor has incomparable advantages in size, integration, and system (Afsarimanesh et al., 2020; Ke, 2020). Currently, sweat collection and quantitative chemical analysis for health monitoring based on microfluidic system is the most practical microsensor technology to supplement or potentially eliminate the blood-based detection methods. This integration limits the entry point of a small group of sweat glands, allowing sweat to spontaneously start, sweat through the microfluidic network and a set of reservoirs, but it is difficult to work without sweat. This problem can be solved by iontophoresis (Dervisevic et al., 2020), that is, by applying a mild electric current to the skin, it can help to release small sweat inducing molecules into the dermis where the sweat glands are located, and specific drugs can also provide a specific pattern of sweat secretion.

Typical microsensors with great potential of W-IoT in the future are as follows: ion sensors, gene sensors, and surface acoustic wave (SAW) sensors. As described by Ke (2020), micro electrochemical chloride sensor has high performance in various chloride concentrations and is suitable for medical research and environmental monitoring. Although the disposable features of these sensors make them unsuitable for long-term condition monitoring, it provides more possibilities for the development of new portable sensor devices. Yang et al. (2019) constructed a new bandage type wearable flexible microfluidic sensor for rapid visual detection of nucleic acid, which is triggered by the body heat (30 °C–37 °C), allowing visual nucleic acid detection within 10 min. This wearable nucleic acid sensor may be of great significance in on-line pathogen detection and molecular damage detection of epidermal cells. And Lamanna et al. (2020) firstly proposed a novel SAW immunosensor based on aluminum nitride for the detection of *Escherichia coli*. But compared with the SAW traveling on aluminum nitride on silicon substrate, the Lamb wave traveling on polymer devices has higher sensitivity. This work demonstrates the high biosensor potential of flexible polymer SAW devices in controlling bacterial contamination. In addition, Su et al. (2020) showed a quartz SAW delay line humidity

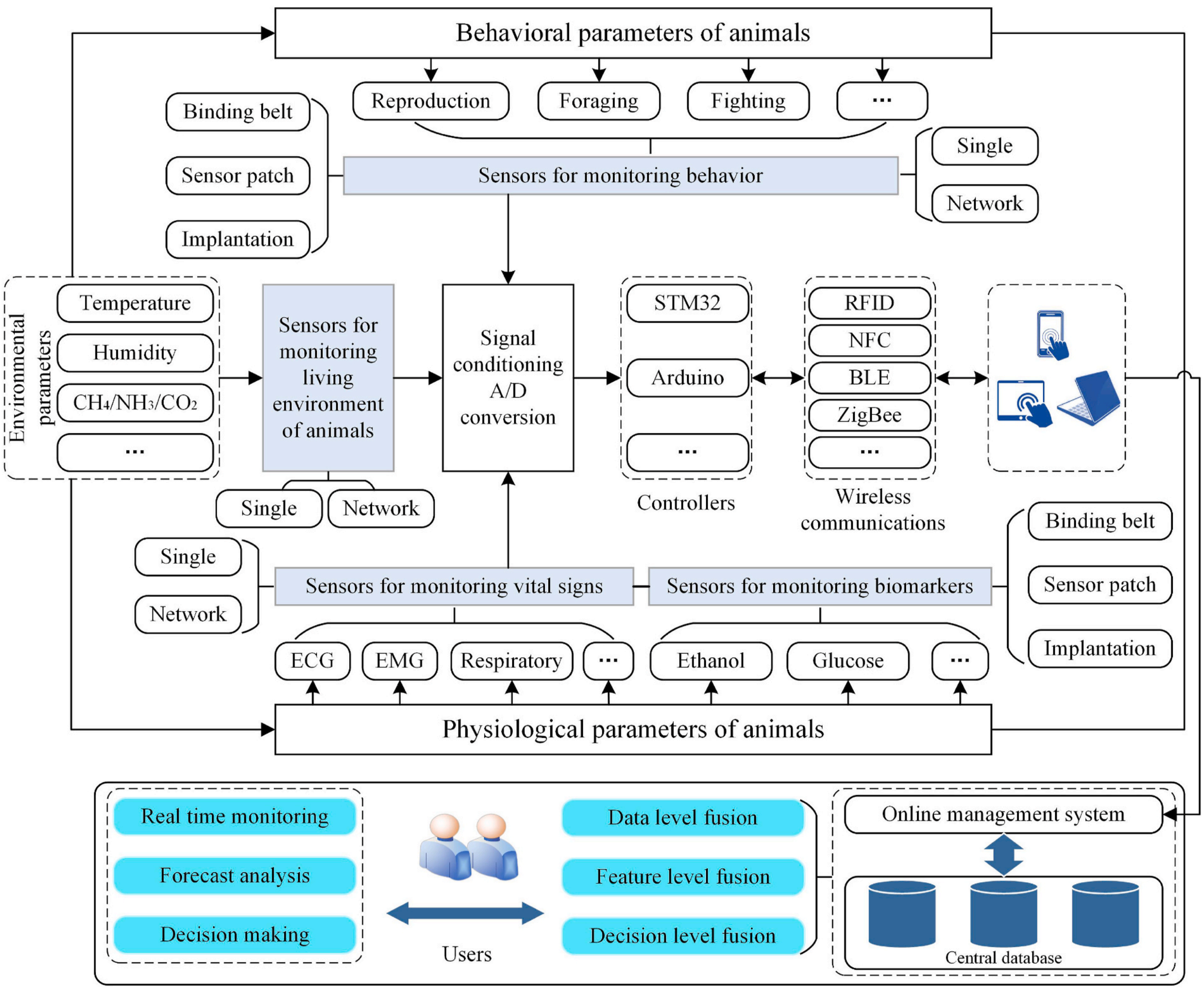

Fig. 6. Working mechanism of multi-sensor information fusion in smart farms.

sensor based on three-dimensional structure of graphene/polyvinyl alcohol/silica film, which showed high sensitivity, especially in the high relative humidity range of 55%–90%, and applied it to respiratory monitoring.

3.1.4. *Intelligent sensors*

Intelligent sensors have been gradually used in wearable health management (Legner et al., 2019; Dervisevic et al., 2020; Nižetić et al., 2020). In particular, (Chua et al., 2013), blood biochemical indicators are the most important monitoring parameters, but it still depends on the detection of high-end equipment and the analysis of professionals, which is inefficient in cost and time. Usually, when measuring blood glucose, one must prick the finger to take blood, and then put the blood sample on the glucose test paper, and finally put the test paper on the electronic blood glucose meter for measurement. At present, some electrochemical blood glucose sensors which are wearable and minimally invasive only need to be attached to the skin surface to accurately measure the blood glucose concentration, and can record the changes of blood glucose, store historical data, and can communicate with mobile phones to obtain real-time blood glucose information. However, the above methods are traumatic. In the future, sensors that can accurately monitor blood glucose level only by touching skin (Yadav et al., 2015) or even inputting voice (Sidorova et al., 2020) can be realized, instead of piercing skin through blood detection method, which requires high intelligence of sensors. Compared with traditional invasive methods, wearable non-invasive intelligent sensors will be more suitable for monitoring active farm animals, because farm animals are usually difficult to control.

3.2. *Multi-sensor data fusion*

In practical application, wearable sensors can obtain lots of information, including the monitoring of movement, behavior, and biomarkers of farm animals. To explain the complex multi-dimensional information provided by these sensors, data fusion can be used to fully express and improve the accuracy. Since the multi-sensor information processed by data fusion has a more complex form, there are essential differences between multi-sensor data fusion and classical signal processing methods (King et al., 2017). By means of fusion, the multi-source information with various relationships can be de forged, de roughened and integrated to obtain more accurate and complete information, and this fusion can also appear at different information levels. However, in the real environment, most wearable systems tend to use multiple sensors of the same or different kind to obtain too much information, and it is difficult to configure the appropriate multi-sensor deployment to obtain the tradeoff between computational complexity and accuracy. The fusion methods are the key contents to improve efficiency and ensure accuracy. Most of the multi-sensor data fusion algorithms are proposed according to specific problems, which can obtain the optimal results for the problems in specific scenarios. For instance, Clapham et al. (2011) proposed a method of cattle feeding behavior based on acoustic analysis, which used high pass filter and Fourier transform to process acoustic signals, and used principal component analysis to classify feature signals, including duration, amplitude, spectrum and

Table 3
Comparative analysis of different monitoring modes for W-IoT in PLF.

Classification basis	Monitoring modes	Applicable parts	Main parameters	Accuracy	References
Wearing ways	Binding belt	Legs, Neck	· Body temperature, Heart rate, Oxygen saturation, Blood pressure, Behavior	Low	Zhang et al. (2019a)
	Sensor patch	Skin surface	· Inorganic salt, Biomarkers, Body temperature, Bending, Pressure, Tension	Medium	Rose et al. (2015); Koh et al. (2016); Gao et al. (2016)
	Implantation	Blood vessel, Intercellular substance	· Inorganic salts, Lactic acid, pH, Blood glucose, Ethanol, Enzymes, Hormones	High	Yoon et al. (2018); Zhang et al. (2019a)
Degree of trauma	Non-invasive	Skin surface	· Body temperature, Heart rate, Blood oxygen saturation, Blood pressure, Bending force, Pressure, Tension	Medium (Sensor patch) Low (Binding belt)	Rose et al. (2015); Koh et al. (2016); Gao et al. (2016); Neethirajan et al. (2017); Zhang et al. (2019a)
	Minimally invasive	Blood vessel, Intercellular substance	· Inorganic salts, Lactic acid, pH, Blood glucose, Ethanol, Enzymes, Hormones	High	
Sensor layout	Single	All the cases described above		Low	Nadimi et al. (2008); Zhang et al. (2019a)
	Network	All the cases described above		High	

energy. Uddin et al. (2020) extracted the features of ECG, accelerometer, magnetometer and other sensor data, enhanced the extracted features through kernel principal component analysis, and the robust features were used to train the deep recurrent neural network model for behavior recognition. Fig. 6 shows the working mechanism of multi-sensor information fusion in smart farms.

Data fusion is based on the independent observation data of multiple sensors, and more effective information can be obtained through composite application and algorithm design, to eliminate the limitation that a single sensor can only obtain partial information of detection target. Specifically, the features of the application of multi-sensor fusion technology in livestock farm are as follows:

- *Strong environmental adaptability*: Generally, the environment of farm is disordered, and the number of farm animals is large and active, which makes it difficult to control comprehensively. The information collected by multi-sensor fusion technology has obvious feature complementarity, covering more space and time, which makes up for the uncertainty of spatial resolution and environment semantics of a single sensor.
- *Wide perception dimension*: The time and space coverage rate of the system is extended by using the homogeneous or heterogeneous data fusion technology of multi-sensor, and the real-time performance and information utilization rate of the system are increased. Especially when some sensors fail, the monitoring system can continue to work.
- *High measurement accuracy*: The combination of multiple sensors can obtain different features of the same target at the same time, reduce the interference of environment, noise, and other factors, and enhance the reliability and accuracy of data.
- *Fast processing speed*: Compared with multiple sensors used alone at the same time, multi-sensor fusion can adopt parallel processing technology and distributed algorithm, which can effectively increase the response speed of the system and improve the real-time performance.
- *Complex structure*: Information fusion system can process more abundant information, which leads to its complex structure, high energy consumption and high cost. Large initial investment has a certain impact on the economic benefits of the farm, but in the long run, it is more conducive to the healthy and sustainable development of livestock products.

4. Biocompatibility of wearable devices

4.1. Wearable methods

Wearable methods directly affect the operability of real-time, dynamic and continuous monitoring of animal health and the stability and accuracy of monitoring results. According to the way of wearing, it can be divided into in vivo and in vitro monitoring, according to the degree of trauma, it can be divided into minimally invasive and non-invasive, according to the layout of sensors, it can be divided into single and network. In addition, the in vitro monitoring mode can be divided into the binding type and the adhesive type. Table 3 presents the comparative analysis of different monitoring modes for W-IoT.

Specifically, the binding type has the advantages of simple and convenient wearing and low price, but it is easy to fall off, greatly affected by the external environment, and has low monitoring accuracy, and is limited to the size of animals (Zhang et al., 2020). Generally small in size, light in weight and easy to operate, the sticking device can integrate non-invasive or minimally invasive monitoring technology (Koh et al., 2016; Rose et al., 2015). When the patch is integrated with the minimally invasive sensor probe, it can penetrate the subcutaneous tissue and obtain high accuracy. Microsensor devices are usually implanted into tissues or organs for in vivo monitoring, which has high precision, is not limited by animal size, and is not easy to fall off, but is expensive and has limited communication capacity. Noninvasive wearable monitoring method has low accuracy, but its advantages are convenient and durable, and it has little impact on daily activities, especially for animal behavior monitoring (Clapham et al., 2011; Pons et al., 2017). The minimally invasive monitoring method has a slight impact on animal health, and it is not easily affected by external factors and the monitoring accuracy is relatively high. More importantly, W-IoT technology has the function of monitoring one or more parameters. In particular, building a sensor network can efficiently collect, transmit and record data (Zhang et al., 2019a), and realize the comprehensive perception of the physiological and environmental information of farm animals, so as to ensure the real-time and reliability of evaluation and decision-making.

4.2. Flexible electronics

In the face of active farm animals, on the one hand, wearable devices should be wear-resistant and stretchable; on the other hand, flexible fit and biocompatibility are also necessary to achieve accurate monitoring and avoid introducing additional stimulation. In recent years, due to new breakthroughs in the research of conductive polymers, organic materials can be transformed from traditional insulators to conductive

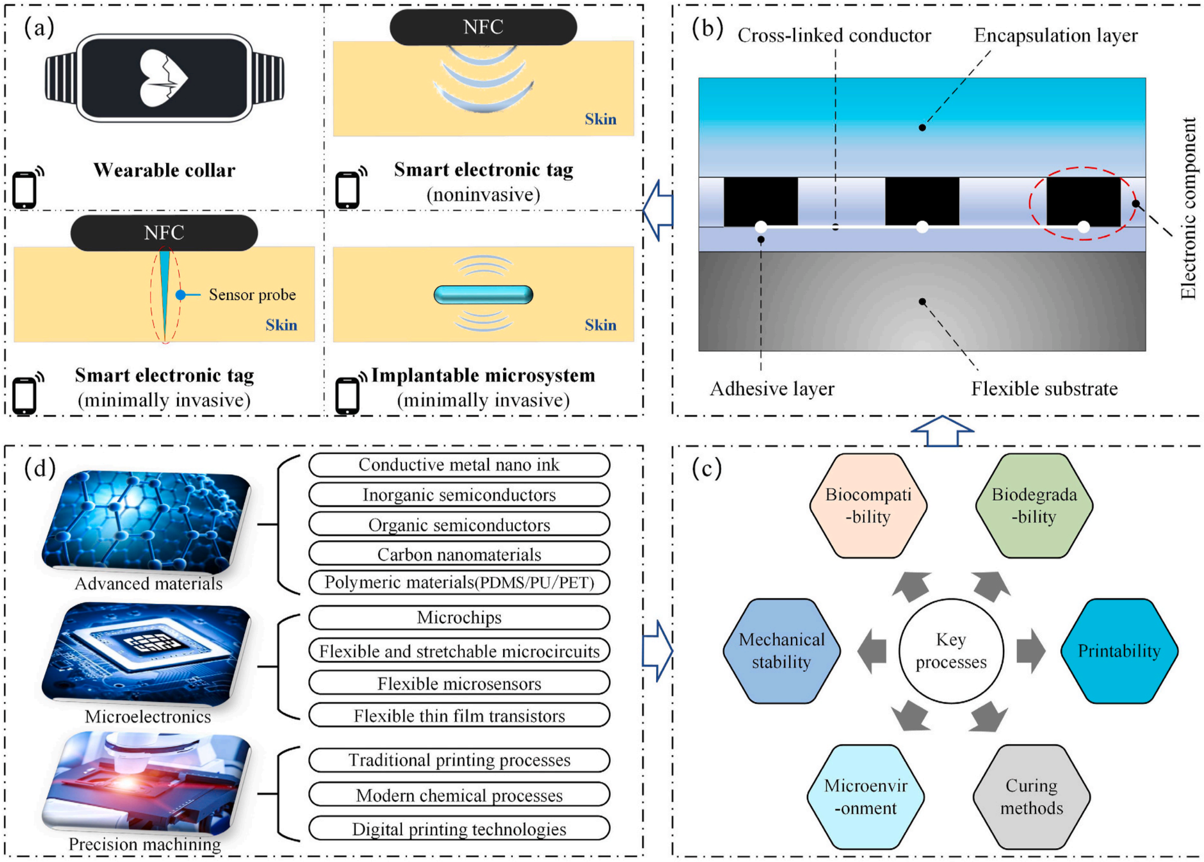

Fig. 7. Technological processes of flexible electronics for W-IoT. (a) Schematic diagrams of four types of W-IoT. (b) Structure diagram of flexible electronics. (c) Key processes of flexible electronics manufacturing. (d) Advanced materials, microelectronics and precision machining technology of flexible electronics.

semiconductors, and coupled with the technical foundation of inorganic materials, flexible electronics have emerged (Lu et al., 2019; Torrisi and Carey, 2018). Compared with traditional rigid or hard electronic materials, wearable flexible electronic devices mainly use materials with flexibility and ductility, and do not cause physical damage under the action of force, and even need to have self-healing function, so the innovation of flexible material technology has become the focus (Dervisevic et al., 2020; Salim and Lim, 2019). Fig. 7 presents the technological process of flexible electronics for W-IoT.

4.2.1. Materials of flexible electronics

Now, there are five kinds of flexible electronic materials, which are metal materials, inorganic semiconductor materials, organic semiconductor materials, carbon materials, composite materials (Fig. 7d). Metal materials are generally used as conductor materials such as gold, silver, and copper, which are mainly used to make electrodes and wires (Cano-Raya et al., 2019; Liu and Wang, 2019). At present, conductive materials used in flexible electronic devices are mainly conductive nano ink, such as nanoparticles and nanowires. Cano-Raya et al. (2019) pointed out that ink based on solid metal particles usually contains about 20%–60% metal by weight. The current challenge is to replace gold and silver particles with other cheaper conductive metals, such as copper, aluminum, or nickel, which are low-cost substitutes for silver ink. However, they are not stable to oxidation and will form insulating oxide, which seriously affect the conductivity of ink. Inorganic semiconductor materials are the most potential candidate materials for fast response and high-resolution pressure sensor materials in the future. For instance (Liu and Wang, 2019), ZnO and ZnS have played a huge role in the field of wearable flexible electronic sensors due to the excellent piezoelectric properties. The representative of organic materials is flexible varistor, because the transistor has perfect signal conversion and amplification performance, which makes it possible to reduce signal crosstalk. Therefore, most of the current research in wearable sensors and artificial intelligence is focused on how to obtain large-scale flexible varistors (Matsui et al., 2019). The carbon materials used in flexible wearable electronic components are mainly carbon nanotubes with high crystallinity, good conductivity and large specific area, and graphene with thin transparency and good conductivity and thermal conductivity (Fu et al., 2018). As the active material of the flexible wearable electronic strain sensor, the size of the flexible wearable electronic strain sensor is limited in a certain range because it is difficult to integrate ordered nano size array in macro scale. In order to make flexible wearable strain sensors have good conductivity in a large strain range, usually elastomers and conductive materials are combined to make composite materials (Lu et al., 2019). The former includes polydimethylsiloxane (PDMS), polyethylene terephthalate (PET), polyimide (PI), polyethylene (PE), polyurethane (PU), etc.; the latter includes graphene, carbon nanotubes, gold nanoparticles, silver nanowires, etc.

4.2.2. Structure of flexible electronics

Flexible electronic devices need not only flexible substrate, but also smaller functional circuits and components on the flexible substrate, and the material and substrate must have good compatibility. Generally, flexible electronics consists of five parts: electronic components, flexible substrate, cross-linked conductor, adhesive layer, and encapsulation layer (Fig. 7b).

1) *Electronic components*: Electronic components are the basis for flexible electronics to realize various functions, including thin film transistors and sensors commonly used in electronic technology (Matsui et al., 2019). There is no essential difference between these electronic components and those of traditional electronic

Table 4
Manufacturing technologies, technical description, manufacturing accuracy and applications of flexible electronics for W-IoT.

Manufacturing Technologies	Technical description	Manufacturing accuracy	Applications for W-IoT	References
Weaving technology	By embedding the conductive fiber into the fabric, the fabric is endowed with certain electrical conductivity.	100 μm in diameter (Ma et al., 2014)	Wearable, flexible, and stretchable conductive fiber/ fabric	Ma et al. (2014)
Impregnation technology	The fabric is impregnated with conductive ink and then dried to form a conductive coating on the surface of the fabric.	Nylon, cotton, and polyester show 34%, 22% and 13% increase in weight respectively after 4th impregnation (Gahlout and Choudhary, 2019)	Wearable, flexible, and stretchable conductive fiber/ fabric	Gahlout and Choudhary (2019)
Screen printing technology	The mesh of the graphic part of the printing plate can pass through the ink, and the mesh of the non-graphic part cannot pass through the ink.	50 μm in width (Liu et al., 2021) 40 μm in width (Tran et al., 2018)	Wearable, flexible, and stretchable conductive fiber/ electrode/circuit/organic components	Liu et al. (2021); Tran et al. (2018)
Electrochemical technology	The conductive material is deposited directly on the surface of the fabric electrode.		Wearable, flexible, and stretchable conductive fiber/ electrode/circuit	Cakici et al. (2017)
Vapor deposition technology	The oxidant is coated on the fabric by dipping or dripping, and then the treated fabric is put into a closed cavity containing monomer.		Wearable, flexible, and stretchable conductive layer/ fiber/electrode	Mittal and Rhee (2018)
Inkjet printing technology	The conductive ink is sprayed onto the printing medium to form conductive lines or functional patterns.	20 μm–50μm in width (Zhang et al., 2016; Tran et al., 2018)	Wearable, flexible, and stretchable conductive electrode/fiber/circuit/thin film transistor, etc.	Zhang et al. (2016); Tran et al. (2018)
Electrohydrodynamic printing technology	Electrohydrodynamic relies on electrostatic force to control the ejection of droplets, spray generated by cone jet mode, or fibers generated by electrospinning, or droplets generated by electric current dynamic injection.	25 μm in width (Jiang et al., 2020) 90 μm in width (Kang et al., 2017)	Wearable, flexible, and stretchable conductive electrode/fiber/circuit/thin film transistor, etc.	Zhang et al. (2016); Jiang et al. (2020); Kang et al. (2017)
Aerosol jet printing technology	The ink is focused and transferred to the printing head by high-speed air flow, and the accurate deposition of nano materials is realized by using the principle of aerodynamics in the printing process.	10 μm in width (Laurent et al., 2018)	Wearable, flexible, and stretchable conductive electrode/fiber/circuit/thin film transistor/photodiode, etc.	Zhang et al. (2016); Laurent et al. (2018)
Laser stripping technology	The conductive material is transferred to the substrate by pulsed laser ablation.	10 μm Gaussian laser spot diameter (Dotan et al., 2021)	Flexible thin film transistor, etc.	Dotan et al. (2021); Joe et al. (2017)

technology. Some of them are made of inorganic semiconductor materials (such as silicon). Because of its brittle material, it is prone to brittle fracture in the process of deformation, so it is usually not directly distributed on the circuit board, but first placed on the rigid cell Island, and then the micro cell Island carrying the components is distributed on the flexible substrate (Matsui et al., 2019). The advantage of this is to protect electronic components from damage during bending or stretching. Some electronic components can also be directly distributed on the flexible substrate, such as some thin film transistors, because of their own features, they can bear certain strain directly without affecting the function. Compared with the traditional microelectronic technology, the use of organic electronic components is a significant feature in flexible electronic technology, in which organic thin film transistors occupy a very important position (Lu et al., 2019; Matsui et al., 2019). The use of organic materials creates conditions for reducing the weight and thickness of components and improving their flexibility and ductility.

2) *Flexible substrate*: Wearable devices are required to have good performance in light, tensile, insulation, corrosion resistance, etc. The flexibility of flexible electronic system is mainly manifested through the substrate, which is the most prominent point that flexible electronic technology is different from traditional electronic technology (Salim and Lim, 2019). In general, PDMS is the preferred substrate material because of its stable chemical properties, good transparency, and good heat resistance (Torrisi and Carey, 2018; Matsui et al., 2019). At the same time, the distinct adhesion and non-adhesion areas under ultraviolet light make it easy to adhere to electronic materials. In addition, PET, PI, PE and PU can also be used as base materials for flexible wearable electronics. Different materials can be used for products with different requirements on flexibility. For example, silicone organic resin with strong flexibility is usually used for electronic skin. However, flexible electronic display requires less flexibility than electronic skin, and PET is often used.
3) *Cross-linked conductor*: As described in reference (Chen et al., 2020), in general, the cross-linked conductor is attached to the flexible substrate in the form of metal film. Electronic components are first distributed on rigid micro cell islands, and many of these micro cell islands are distributed on the flexible substrate. These micro cell islands do not exist independently, they are connected by cross-linked conductors, thus forming a complete flexible circuit, that is to say, the cross-linked conductor acts as a wire in the flexible electronic system. Han et al. (2019) believe that conductive elastomers require more renewable bio-based materials from natural crops than the existing unsustainable materials. Nonconductive elastomer matrices have enhanced mechanical and electrochemical properties, especially natural polymers, but it is still a challenge to construct effective and stable conductive networks.
4) *Adhesive layer*: As flexible electronic components are inevitably subjected to higher-than-normal temperature environment, constant tension, compression and bending deformation during assembly and use. The adhesive layer is particularly important for the combination of cross-linked conductors and flexible substrates, and should have heat resistance, bonding strength, stretching and bending capabilities (Li and Wong, 2006). At present, the adhesive layer materials commonly used in flexible circuits mainly include acrylic resin and epoxy resin.
5) *Encapsulation layer*: The encapsulation layer mainly protects the flexible circuit from dust, moisture, or chemicals, and also reduces the strain of the circuit during bending or stretching (Atiqah et al., 2020; Kim et al., 2019). Recent studies have shown that the encapsulation layer can reduce the stress intensity at the edge of the rigid micro cell island in the flexible circuit and inhibit its separation from the flexible substrate. According to the features of flexible electronic

Table 5
Features and application scenarios of different communication technologies for W-IoT in PLF.

Communication modes		Main features	Application scenarios	References
WPAN [a]	RFID	Ultra-short-range radio frequency communication, small size, no power or low power consumption, independent of external network, portable, low cost, unable to directly connect to the cloud, slow communication speed, etc.	· Minimally invasive sensor patch · Noninvasive sensor patch · Implantable microsystem	Salim and Lim (2019); Legner et al. (2019); Yoon et al. (2018)
	NFC	Compared with RFID, NFC has the features of shorter distance, higher bandwidth, lower energy consumption point-to-point communication, etc.	· Minimally invasive sensor patch · Noninvasive sensor patch · Implantable microsystem	
	Bluetooth	Short range wireless communication, independent of external network, portable, low power consumption, low complexity, low cost, unable to directly connect to the cloud, slow transmission speed, weak networking ability, etc.	· Wearable collar · Other binding wearables	Salim and Lim (2019); Legner et al. (2019); Muzammal et al. (2020)
WLAN [b]	Wi-Fi	Short range wireless communication, Internet access, low complexity, high data rate, limited connectivity, and slightly higher cost, power consumption, etc.	· Wearable collar · Other binding wearables	Salim and Lim (2019); Legner et al. (2019); Park et al. (2019)
	ZigBee	Short distance wireless communication, low complexity, self-organizing network, low power consumption, low data rate, low cost, etc.	· Wearable collar · Other binding wearables	Nadimi et al. (2008); Legner et al. (2019); Park et al. (2019)
WWAN [c]	GPRS/3G/4G	Long distance wireless communication, high transmission rate, high price but flexible, high resource utilization, always on-line, high power consumption, large volume, etc.	· Wearable collar · Other binding wearables	Popli et al. (2021); Abbas et al. (2020)
	5G	Compared with GPRS/3G/4G, 5G has higher bandwidth, lower delay, more massive access capability, higher power consumption, cost, etc.	· Wearable collar · Other binding wearables	
LPWAN [d]	NB-IoT	Long distance wireless communication, authorized frequency band, cellular networking, wide coverage, low power consumption, large capacity, multi node, low cost, etc.	· Wearable collar · Other binding wearables	Abbas et al. (2020); Dawaliby et al. (2019); Popli et al. (2021)
	LoRa	Long distance wireless communication, unauthorized frequency band, independent network construction, low power consumption, large capacity, low cost, etc.	· Wearable collar · Other binding wearables	

[a] Wireless Personal Area Networks.

[b] Wireless Local Area Networks.

[c] Wireless Wide Area Networks.

[d] Low-Power Wide-Area Networks.

system, the encapsulation layer should be able to withstand long-term deflection, so the package materials and the substrate materials must meet certain requirements of fatigue resistance. The materials commonly used for encapsulation layer are acrylic resin, epoxy resin, PI, etc. (Majee et al., 2015).

4.2.3. Manufacturing technologies of flexible electronics

There are two main manufacturing strategies for flexible electronics: one is to transfer the electronic components to the flexible substrate by transfer printing; the other is to directly prepare electrical functional components on the substrate surface by printing. The former is mainly based on silicon-based electronic technology, through clever transfer processing to obtain flexible circuits, this method still cannot get rid of the complexity of the manufacturing process. And the latter is the current focus of the development of flexible electronics, that is, through different printing processes on flexible or non-rigid substrates, the predesigned graphical structure is printed with functional ink for connecting electronic components. As described in the literatures (Sreenilayam et al., 2020; Ryan et al., 2020; Joe et al., 2017), currently, the main technologies or methods that can be used in flexible electronic manufacturing include knitting, impregnation, screen printing, electrochemistry, vapor deposition, ink-jet printing, electrohydrodynamic printing, aerosol jet printing and laser stripping. Table 4 summarizes the manufacturing technologies, technical description and applications of flexible electronics for W-IoT.

5. Sustainability monitoring of wearable systems

5.1. Communication technologies

Currently, wearable technologies are basically designed for the scenarios of human, not animals. Since Bluetooth and NFC communication

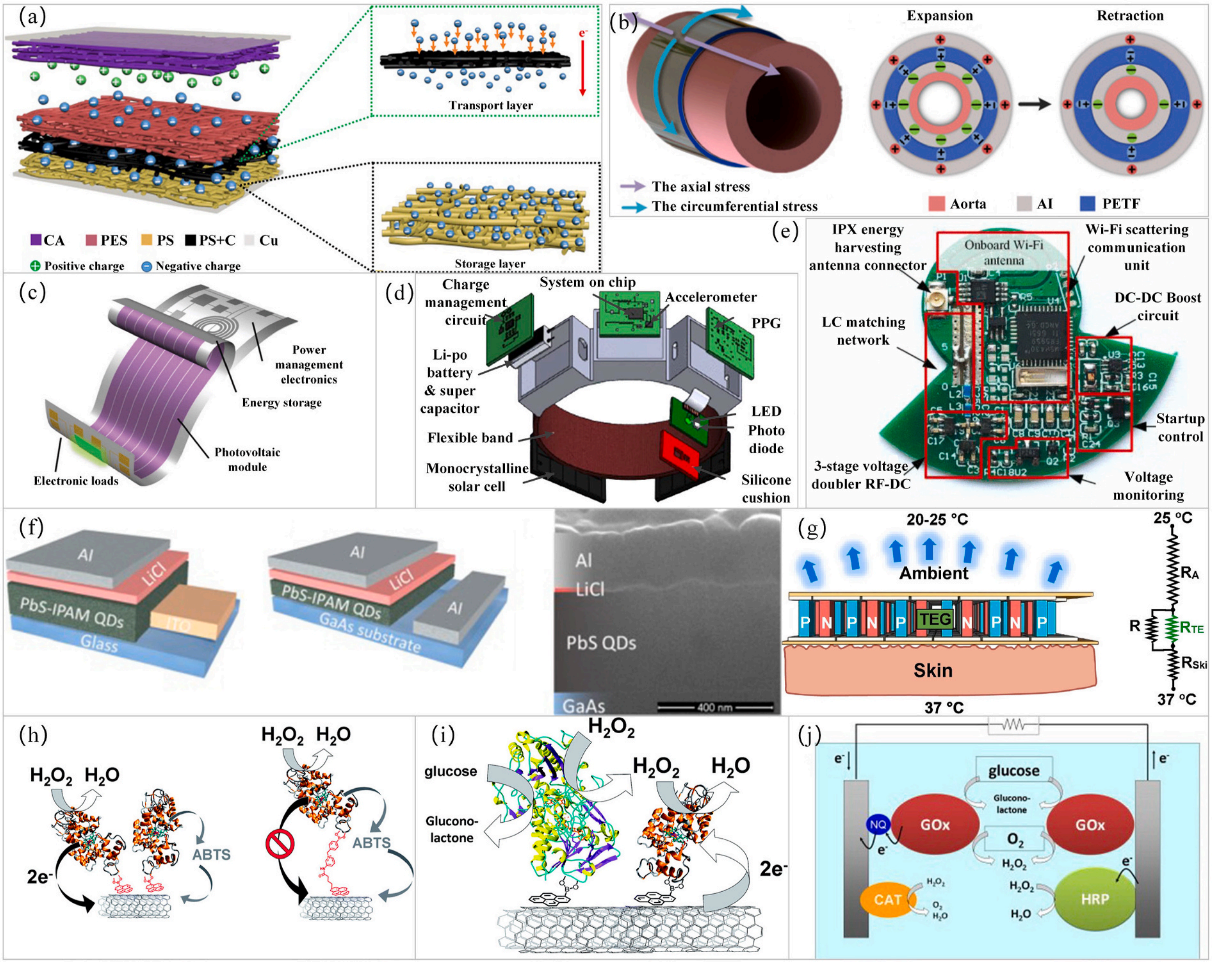

Fig. 8. The research cases of self-powered technologies for wearable systems. (a) Schematic illustration of triboelectric charge transport and storage process of three-layer triboelectric nanogenerator (Li et al., 2018). (b) Schematic illustration of induced charge distribution in implantable self-powered blood pressure monitoring telescopic device based on piezoelectric film (Cheng et al., 2016). (c) Schematic illustration of fully printed, flexible, integrated photovoltaic system (Ostfeld and Arias, 2017). (d) Schematic illustration of photovoltaic module, battery, supercapacitor, and pulse oximeter integrated into wristband (Dieffenderfer et al., 2014). (e) Prototype of the passive Wi-Fi communication equipment based on RF energy harvesting (Tang et al., 2019). (f) Schematic illustration of a device and its material composition for converting heat radiation into electrical energy (Ghomian et al., 2018). (g) Schematic illustrations of thermal circuit of thermoelectric generator for body heat harvesting. R_{Ski}, R_{TE}, R, and R_A are the thermal resistance of the skin, the thermoelectric generator, the filler thermal resistance, and the air, respectively (Nozariasbmarz et al., 2020). (h), (i) and (j) Schematic illustrations of glucose biofuel cell: the functionalization of multiwalled carbon nanotube electrodes with glucose oxidase and horseradish peroxidase for the reduction of O_2 into H_2O (Agnès et al., 2013; Reuillard et al., 2014).

have low energy consumption, small size, and convenient use, which are very suitable for personal daily use, the communication methods on wearable devices are mostly Bluetooth and NFC (Salim and Lim, 2019; Muzammal et al., 2020). But for animal health monitoring, especially in large-scale breeding bases, more efficient and practical data communication solutions should be constructed (Zhang et al., 2019a). The specific features and application scenarios of different communication methods are shown in the table below. Each mode has its advantages and disadvantages. For example, RFID and NFC communication technology are suitable for wearable patches and embedded micro systems, and are particularly practical and convenient for monitoring blood glucose, blood lactate, ion concentration, etc. (Zhang et al., 2019a); Bluetooth and ZigBee communication technology is suitable for wearable collar, which can be worn on the neck of animals to monitor vital signs such as heart rate, body temperature and blood oxygen saturation, but the communication distance is short and the communication speed is slow (Nadimi et al., 2008; Salim and Lim, 2019; Muzammal et al., 2020); Although 5G technology is also suitable for wearable collar, and its communication distance is long and its speed is fast, but its high power consumption and high cost limit its large-scale application in the farm (Abbas et al., 2020; Popli et al., 2021). Both NB-IoT and Lora are low-power wide-area Internet of Things technologies, which can deploy a large number of monitoring nodes in large-scale farms (Abbas et al., 2020; Popli et al., 2021). The former can be directly deployed on the existing wireless communication base stations, including 5G communication standard, without bearing the cost of base station construction, but the network quality depends on the base station built by the operator, and the network rental fee should be paid; the latter is the enterprise self-built network, which can expand the network according to the service requirements, but needs to bear the construction cost of the base station. Table 5 describes the comparison of features and application scenarios of different communication technologies for W-IoT.

5.2. Self-powered technologies

Obviously, the energy supply of wearable devices or systems is undoubtedly the key point to determine whether they can work normally, accurately, and sustainably. Although low-power consumption electronic circuit technology and battery technology (especially lithium battery) have been well developed (Sodhro et al., 2019), the use of wearable and implantable devices is still limited to the life of embedded batteries. This requires periodic battery replacement, but for

Table 6
Features and application scenarios of self-powered technologies for W-IoT in PLF.

Energy sources	Max. energy density	Features	Typical potential applications	References
Triboelectric	~13 μW/cm^2 under a frequency of 3 Hz	· Low output voltage · Easy to expand · Easy to manufacture · Low cost · Low power density	· Wearable self-powered power generation devices with flexible, stretchable, washable and breathable · Self-powered touch devices	Li et al. (2018)
Piezoelectric	~1.2 μW/cm^2 in vivo and ~37 mW/cm^2 in vitro	· Low power density · Low output voltage · Highly sensitive · Simple in structure	· Wearable pressure sensor · Wearable pacemaker · Wearable accelerometer · Piezoelectric generator	Dagdeviren et al. (2014); Ghomian and Mehraeen (2019)
Photovoltaic	~2.2 μW/cm^2 on the skin in a dark room and ~0.36 μW/cm^2 under infrared excitation	· High reliability and efficiency · Easy to manufacture · Low cost · Limited by ambient light	· Wearable collar · Wearable Bracelet · Wearable patch	Ghomian et al. (2018); Ghomian and Mehraeen (2019)
Radio frequency	Up to 15 μW/cm^2	· Easy to deploy · Very low power · Low cost · Current does not last	· Wearable patch · Implantable microsystem · Wearable collar	Chong et al. (2019)
Thermoelectric	60 μW/cm^2 in indoor and 600 μW/cm^2 at 0 °C	· Higher power density · Easy to expand · Low cost · Limited by ambient temperature	· Wearable patch · Wearable collar · Wearable Bracelet	Ghomian and Mehraeen (2019)
Biofuels	Maximum catalytic current up to 504 μA/cm^2	· Specificity · High efficiency · Hard to control · Harsh reaction conditions	· Implantable microsystem · Wearable patch	Agnès et al. (2013)

implantable devices, each battery change can be an injury. Some devices may need to sacrifice performance and functionality to extend battery life. Self-powered may be a particularly important feature when battery replacement or charging is not possible or impractical. At present, the autonomous energy acquisition technology based on triboelectricity, piezoelectric effect, photoelectric effect, radio frequency induction, thermoelectric effect, electrochemical reaction, and bioelectricity has been widely concerned (Nozariasbmarz et al., 2020; Tang et al., 2019; Ghomian et al., 2018; Ostfeld and Arias, 2017; Reuillard et al., 2014). As animal body heat energy, body movement and biological substances (enzymes, hormones, glucose, etc.) are abundant energy sources of animal body, so it is a reliable and practical solution to obtain energy from available resources in animal body and supply energy to equipment or system completely or partially. Fig. 8 presents the research cases of

Table 7
Specific benefits of the application of W-IoT in PLF.

Benefits	Description	Performance	References
Precise perception of information	· Noninvasive flexible photoelectric skin sensing improves biocompatibility and detection accuracy	· HR (mean difference = 0.1 bpm, SD = 2.55 bpm) and RR (mean difference = 0.3 bpm, SD = 0.95 bpm)	Chung et al. (2019)
	· Quantitative measurement of animal behavior to promote precision breeding and management	· The walking behavior is classified with 96% sensitivity, 99% specificity, 91% precision and 98% accuracy	Achour et al. (2019)
	· Microfluidic biosensors can be used for pathogen monitoring and quantitative extraction	· A linear relationship between the impedance changes and the concentrations of Listeria from 1.9 × 10^3 to 1.9 × 10^6 CFU/ml was obtained. The limit of detection of this biosensor was 1.6 × 103 CFU/ml	Gattani et al. (2019)
	· Noninvasive biological sensing of sensor array improves detection diversity and accuracy	· The relative standard deviation of the sensitivity of Na+ and K+ sensors is about 1%, while that of glucose and lactic acid sensors is about 5%.	Gao et al. (2016)
	· Multi-sensor information fusion reduces system error and improves overall accuracy and efficiency	·Obtain 98% accuracy when the tree depth is equal to 15, number of estimators is 40, and 8 features are considered for the prediction task	Muzammal et al. (2020)
	· Intelligent perception promotes the precision and intelligent development of livestock breeding	· By recording the calls of broilers within 38 days, the peak frequency (Hz) of 600 calls randomly selected can be determined for diagnosis of feeding status	Astill et al. (2020)
Traditional way	· Manual data acquisition and manual data recording	· High requirements for personnel's breeding experience, low accuracy of data collection and low operation efficiency	
	· The biochemical indexes of blood were collected in	· The data accuracy is greatly affected by the operation	

(continued on next page)

Table 7 (*continued*)

Benefits	Description	Performance	References
	an invasive and discontinuous way	experience and professional knowledge of employees	
Biocompatibility	· The diversity of wearable ways can improve the compatibility and reliability of comprehensive perception of the physiology of breeding animals	· The accuracy of body temperature, blood pressure and heart rate can be reached respectively ± 0.05 °C、 ± 3 mmHg and 1.0%	Zhang et al. (2019a)
	· The wearable stretchability can improve the biocompatibility	· The stretchability based on resistance mechanism can reach 460%, and that based on capacitance mechanism can reach 700%	Lu et al. (2019)
	· The wearable bending capacity can improve the biocompatibility	· 8 mm bending for 10,000 cycles (PET); 10,00,000 cycles (PEN)	Salim and Lim (2019)
	· The wearable microfluidics technology can improve the biocompatibility	· The detection limit of nucleic acid was 10 copies/μ L	Yang et al. (2019)
	· The fitting ability of wearable biosensors can improve the biocompatibility	· With 96% accuracy at 50 mM Na^+(in vitro tests)	Rose et al. (2015)
Traditional way	· Most use bundled wearable devices to manage animals	· The Bundled wearable device is not conducive to effectively fit the skin and is easy to cause stress reaction	
	· Manual data acquisition and manual data recording	· Manual information collection is easy to cause stress reaction	
Sustainability	· Flexible photovoltaic technology improves the sustainability monitoring	· The PCE of flexible perovskite solar cells based on carbon nanomaterials can reach 18.1%	Fu et al. (2018)
	· Piezoelectric power generation technology improves the sustainability monitoring	· With typical power density of 64.9 $\mu W/cm^2$	Nozariasbmarz et al. (2020)
	· Magnetic induction power generation technology improves the sustainability monitoring	· With typical power density of 8.7–2100 $\mu W/cm^3$	
	· Triboelectric nanogenerators power generation technology improves the sustainability monitoring	· With typical power density of 50 mW/cm^2	
	· Biofuels technology improves the sustainability monitoring	· Maximum catalytic current up to 504 $\mu A/cm^2$	Agnès et al. (2013)
Traditional way	· Powered by lithium batteries or disposable zinc-manganese batteries	· Charging is troublesome, bulky and unsustainable	
Animal welfare	· W-IoT improves the level of intelligence, informatization and precision of livestock farming	· It is beneficial to health management, disease early warning, precise feeding and precise milking of farm animals	Lovarelli et al. (2020)
Traditional way	· Manual data acquisition and manual data recording	· Manual operation often causes animal discomfort, even stress response, and low efficiency	

self-powered technologies for wearable systems. However, these self-generating technologies mentioned above are still in the development stage due to their low energy density and low power output, and are limited by the integration of low-power circuits. With the progress of material science and manufacturing technology, we believe that micro power generation devices can generate enough electricity for some implantable and wearable electronic devices. Table 6 shows the features and application scenarios of self-powered technologies for W-IoT in PLF.

6. Benefits, challenges and prospects of W-IoT in PLF

6.1. Benefits

W-IoT, as an extension of IoT technology, has been widely used in disease diagnosis, medical rehabilitation and other fields due to the function of real-time data monitoring and health status analysis. Similarly, it can also be applied to the health management of farm animals. W-IoT has the basic features of IoT technology, but also has its unique advantages for farm animals, it can be summarized technically as follows (Specific benefits are shown in Table 7):

- Wearable sensors have the features of small size, light weight, low energy consumption, convenient integration, strong adaptability, flexibility, biocompatibility, etc.
- Information perception will not be limited to environmental indicators but will focus on the physiological and behavioral status of farm animals.
- W-IoT can use bioenergy and behavioral movement to realize self-power supply.
- Attaching or implanting wearable microsystems to farm animal bodies can achieve precise monitoring recording, and prediction.
- W-IoT has good maintainability and expansibility, and can quickly arrange, adjust and collect massive data at almost any time, places and any environmental conditions.
- Docking big data and cloud computing technology to realize intelligent control, remote management, and precise decision-making.

6.2. Challenges

There are some challenges in the practice and application of any emerging technology. With the development of society, sustainable

Table 8
Specific challenges of the application of W-IoT in PLF.

Challenges	Description
Technical factors	· Most of the advanced sensors are only for human research and application, and rarely for professional testing of animals, especially farm animals. In the literature of wearables and IoT retrieved, less than 7% involved farm animals. · Biosensors have high detection accuracy and high specificity, but the detection continuity is poor, and sensitive substances are easy to fail. · Physical sensors are efficient and easy to obtain continuous data, but the accuracy is low. Some of the heart rate errors can reach 10%, and the blood pressure error is larger, which needs further breakthrough. · Multi-sensor data fusion has high accuracy, but the structure is complex and the loss is high, which needs to be further optimized. · Although animal behavior research has achieved initial success, it still needs a lot of original data support. In the questionnaire survey of employees, about 47% support behavior research can obtain certain application value. · The development of wearable sustainable power supply technology has not made a key breakthrough, the self-powered energy density is low, and the endurance is weak.
Economic factors	· The infrastructure construction of the farm is relatively backward, the initial investment burden is large, and it is difficult for relevant enterprises to accept in a short time, especially for small-scale farmers. In the survey, about 78% of workers in large enterprises are willing to update information technology, and more than 90% of small-scale farmers are against the investment of information technology. · The technical expenditure of livestock products is often borne by the bottom practitioners, and the income distribution is uneven. · Although people have higher requirements for food safety and animal welfare, practitioners cannot grasp the benefits. 87% of farmers do not understand the concept of animal welfare, but 93% of practitioners think that food safety is important.
Quality of personnel	· The working population tends to be elderly. Among the surveyed employees, 19% are between 20 and 39 years old, 45% are between 40 and 59 years old, and 34% are over 60 years old. · The employees have a low educational background. Among the employees based on the survey, 83% have a junior high school degree or below, 11% have a high school degree, 5% have a junior college degree or a bachelor's degree, and 1% have a master's degree or above.
Policy factors	· PLF and smart farms have been proposed, but the scale effect has not been formed, so it is necessary to increase support for leading enterprises. · Although the government has issued relevant documents on animal welfare, there is no clear definition from the legal point of view, and the attention paid by practitioners is insufficient.

development will lead to the long-term and stable social economy in the future. At present, the advantages of W-IoT are only reflected in the application and diagnosis of human beings, and animal testing is rarely conducted. Table 8 shows the specific contents.

6.3. Prospects

Based on the existing research results and the application of wearable technology in human body, this paper summarizes the following development trends of W-IoT for PLF in smart farms.

- Wearable sensor technologies: towards the direction of high precision, low price, flexibility, miniaturization, intelligence and biocompatibility, making it more suitable for large-scale precise monitoring and low-cost application of farm animals.
- Wearable information processing technologies: multi sensor data fusion technology based on big data analysis will be widely used to obtain and mine more valuable information (such as feeding, milking, disease, breeding, etc.) to better promote precision farming and intelligent farming.
- Wearable communication technologies: gradually towards the development of smaller, lighter and lower energy consumption of integrated modules. On the premise of satisfying data recording, short distance wireless communication and long-distance wireless communication coexist. Among them, short-distance communication is represented by Bluetooth and ZigBee, while long-distance communication is represented by NB-IoT (5G standard), etc. In addition, RFID/NFC technology is also an important part of precision farming, which is mainly used for the precise collection and recording of front-end data of physiological indicators in quality traceability system.
- Wearable monitoring modes: from single parameter to multi parameter monitoring, in vivo to in vitro monitoring, trauma detection to minimally invasive or non-invasive monitoring, single sensor to multi-sensor network monitoring, and pay more attention to the influence of sensor distribution form and location on the operability of monitoring process and the accuracy of monitoring results.
- Wearable power supply: at present, the monitoring mode and efficiency of the large-scale deployment of the W-IoT system for farm animals are limited by the power supply, and the thermal energy of moving objects, mobile mechanical energy and biomass fuel are rich energy sources, which provides unlimited possibilities for the development of self-powered technology.

In short, as the basic platform of network construction and biocompatibility, the integration of intelligent sensing, biocompatibility, low-power electronic circuit, data fusion, energy-efficient self-power supply and electric energy storage technologies into the W-IoT is the premise of precise and intelligent monitoring. However, it cannot be ignored that, different from wearable products on human body, information-based precise monitoring and health assessment for large-scale farm animals should take into account the cost, and must maximize economic benefits and promote sustainable development on the premise of ensuring animal health and animal welfare.

7. Conclusion

The Internet of things connects sensors, controllers, operators and objects with communication technologies such as local network or Internet to form an information-based, automatic, and intelligent network. Therefore, the essence of the Internet of Things is to connect the units that originally worked independently and obtain the effective information of the units so that they can be operated in a unified manner. W-IoT technology, as an extension of Internet of things technology, has been widely used in disease diagnosis, medical rehabilitation and other fields due to the function of real-time data monitoring and health status analysis. This paper summarizes the features of W-IoT technology, believes that W-IoT will be beneficial to the development of PLF, and puts forward precise perception of information, biocompatibility of wearable devices, and sustainability monitoring are necessary contents of W-IoT technology for sustainable and precise livestock farming. However, as the livestock farming is still in the process of intensive, information and sustainable development in China, the application and achievement transformation of W-IoT in livestock farming is relatively slow. In the long run, the development of information monitoring technology will be continuously upgraded in livestock farming, especially the development and application of precision and intelligence.

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Declaration of competing interest

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