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Review

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Research and application progress of electronic ear tags as infrastructure for precision livestock industry: a review

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Abstract

With the rapid development of modern livestock farming, animal electronic ear tags (AEET), as animal identification and tracking tools based on radio frequency identification technology, are playing an increasingly important role in precision livestock management. This review summarizes the latest technological advancements in AEET, including material innovations, design improvements, and manufacturing process enhancements, and explores their wide-ranging applications in production management, food traceability, breeding optimization, behavior recognition, and disease monitoring. Additionally, the article highlights the main challenges faced by AEET, such as durability in harsh environments, data security, and cost-effectiveness. Furthermore, it looks ahead to future development trends, including the integration of Internet of Things and blockchain technologies to further enhance the precision and sustainability of livestock farming. By reviewing the current status and future directions of AEET, this review provides references for researchers and practitioners aiming to improve the efficiency and sustainability of modern livestock industry.

Keywords: Electronic ear tags, precision livestock industry, production management, food traceability, behavior recognition, disease monitoring

1. INTRODUCTION

The importance of animal electronic ear tags (AEETs) in modern animal husbandry is becoming increasingly prominent, and their development history also reflects the progress of livestock technology and the transformation of management models. AEETs are devices that use radio frequency identification (RFID) technology to identify and track individual animals, with the advantages of large information storage capacity, fast identification speed, and long service life.

The "2024-2030 Global and China Animal Electronic Tag Industry Research and Development Trend Analysis Report" reveals that with the evolution of RFID technology and Internet of Things (IoT) applications, electronic ear tags now go beyond quick animal identification. They collect data on animals' growth and health, and connect with farm management systems to realize automated and smart animal health management. To boost durability and comfort, manufacturers are also enhancing the design of electronic ear tags for better animal wearability. Additionally, the report delves into the supply - demand dynamics, major production and consumption regions of the global and Chinese animal electronic tag markets, and explores market development trends, offering all - encompassing market intelligence and in - depth analysis. This proves highly beneficial for grasping market demands and the future trajectory of animal electronic tags.

Early electronic ear tags were primarily used for scientific research and small-scale trials, where researchers gradually verified their feasibility under different animal species and environmental conditions. Babot *et al.* compared the performance of visual and electronic identification devices in pig farms and found that electronic ear tags had advantages in terms of identification accuracy and durability[1]. With the continuous advancement of RFID technology, the performance of electronic ear tags has been significantly improved, and their application range has gradually expanded. Research by Eradus *et al.* revealed that in the grazing environment of the farm, electronic ear tags demonstrated superior performance, capable of accurately identifying each individual animal[2]. In recent years, with the introduction of emerging technologies such as the IoT and blockchain, electronic ear tags have gradually achieved interconnectivity with smart devices, constructing a more comprehensive animal management information system. Research by Liu combined blockchain and IoT technology to design a breeding information monitoring system for free-range sheep, verifying its efficiency and stability in practical applications[3].

Leveraging integrated RFID technology, AEET has greatly enhanced the efficiency of breeding enterprises in record management, production performance tracking, and the execution of breeding plans. Research by Boonsong further revealed the broad application prospects of electronic ear tags in smart agriculture; he successfully integrated embedded RFID terminal devices with IoT technology, achieving precise monitoring of animal body temperature and real-time location[4]. By tracking the health status and movement paths of animals in real time, breeding enterprises can take immediate action at the first sign of disease, effectively reducing the risk of epidemic spread. Research by Huang *et al.* clearly demonstrated the high practicality of electronic identification systems in the health monitoring of pig herds[5]. Tobin *et al.*, on the other hand, assessed the health status of sheep, beef cattle, and dairy cows under different activity states by applying accelerometers with electronic ear tags[6]. This integrated application of cross-technology provides a more solid and scientific basis for formulating disease prevention and control strategies.

The application of AEET not only optimizes the efficiency of animal management but also generates significant comprehensive benefits in various dimensions such as disease prevention and control, and food safety. Research by Adrion *et al.* indicated that monitoring growing and finishing pigs with UFH-RFID ear tags has shown that monitoring with electronic ear tags effectively enhances production efficiency and product quality[7]. At the same time, the research and application of electronic ear tags continue to deepen. Liang *et al.* used an RFID-based distributed framework to model and implement traceability in the beef supply chain in China, vividly demonstrating the broad application prospects of electronic ear tags in achieving full traceability from farm to table[8]. A study by Gaja *et al.* compared the performance of electronic ear tags and visual ear tags under different breeding conditions for camels, and the results showed that electronic ear tags demonstrated clear superiority in animal identification and management[9]. Research by Ait-Saidi *et al.* focused on the application effects of electronic identification in dairy cow and meat sheep production, emphasizing its great potential in improving breeding efficiency and management levels[10]. Schoenecker *et al.* assessed the performance of wild horses and camels in captivity using radio collars, further confirming the important application value of electronic ear tags in environmental monitoring and animal health management[11]. These studies not only showcase the application effects of electronic ear tags in different animal species but also reveal their potential in improving breeding efficiency and animal welfare. The typical structure of electronic ear tags is shown in Figure 1.

2. REVIEW OBJECTIVE

As an emerging and increasingly important technological means, electronic ear tags play an increasingly critical role in modern animal husbandry. This paper aims to comprehensively summarize the research progress of AEET, attempting to sort out the status of AEET in terms of technological development, application scenarios, and challenges faced, to provide references for future research and application.

3. THE TECHNOLOGICAL DEVELOPMENT OF AEET

3.1. The development of raw materials for ear tags

Traditional AEETs often use metal materials, which, although they had high strength and durability, showed many problems in practical applications. For example, metal materials are susceptible to corrosion, especially in humid environments, and have a short service life; moreover, the weight of metal ear tags is relatively high, which may affect the animals' activities to some extent.

In recent years, with the rapid development of material science, new types of composite materials have begun to be widely used to manufacture AEET. These composite materials are usually made by combining polymer matrices with various reinforcing materials (such as carbon fiber, glass fiber, *etc.*), and they exhibit many advantages, including lightweight, high strength, and excellent corrosion resistance. Stainless steel is often used in manufacturing metal parts of electronic ear tags, due to its biocompatibility, corrosion resistance, and mechanical strength. It remains stable in complex farming environments, has a long service life, and is non-toxic to livestock. Nanoclay-polymer nanocomposites, formed by blending nanoclay with a polymer matrix, have a unique lamellar structure and high specific surface area. They boost the material's mechanical properties, thermal stability, and barrier properties, giving electronic ear tag materials good gas and water-resistant properties. This enhances the tags' stability and reliability in tough conditions. Edwards *et al.* pointed out in their research that electronic ear tags made from new composite materials demonstrated excellent durability and stability in the field of sheep welfare[12]. This innovation in materials not only significantly extends the service life of the ear tags but also effectively reduces the potential burden on animal activity [Table 1].

New applications have also brought a series of other advantages. First, the lightweight characteristic of composite materials minimizes the impact of ear tags on animal activity, helping to maintain the normal physiological state and living habits of animals. Simmons' research indicated that in herds of cattle, sheep, and pigs using lightweight electronic ear tags, there is no significant difference in the amount of activity and behavioral patterns compared to the control group without ear tags[14]. This suggested that ear tags made from new materials have high biocompatibility in practical applications. Secondly, the corrosion resistance of composite materials is significantly better than that of metal materials. In the livestock environment,

Table 1. The impact of ear tags made of different materials on animal ears

Ear tag type	The impact on animal ears	Ref.
Metal material	Out of 298 ears with metal tags, 86 had only mild lesions	Edwards *et al.*, 1999[12]
Plastic loop rigid one-piece	Out of 93 ears, 27 had mild lesions	
Polyester ammonia material	Out of 51 ears labeled with plastic, 9 developed lesions	Johnston *et al.*, 1996[13]
Ketchum type	Out of 60 ears, 37 developed lesions	

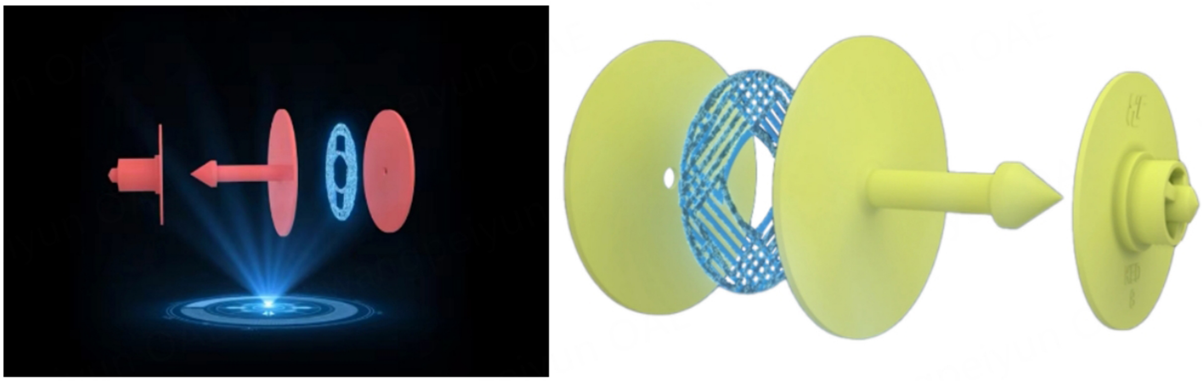

Figure 1. Schematic diagram of electronic ear tag.

animal ear tags are often exposed to various harsh conditions, such as high temperatures and humidity. Traditional metal ear tags are prone to corrosion in these environments, leading to ear tag failure. In contrast, new composite materials can effectively resist the effects of these environmental factors, maintaining the functional integrity and good appearance of the ear tags. Chung *et al.* pointed out that electronic ear tags made from new composite materials have shown good stability and reliability under different climatic conditions[15].

Additionally, new types of composite materials also exhibit good processing performance and high design flexibility. By finely controlling the composition and structure of the materials, we can create various shapes and functions of AEET that could be created to better adapt to the specific needs of different types of animals. A comparative study conducted by Caja *et al.* on electronic identification devices revealed that electronic ear tags made from new composite materials perform better in sheep management than traditional metal ear tags[16]. This flexibility in design not only greatly enhanced the practicality and adaptability of the ear tags but also effectively reduces production costs and subsequent maintenance expenses.

3.2. The updates of design concept

With the advancement of technology and the modernization demands of animal husbandry, the design philosophy of AEET is undergoing profound changes. When designing electronic ear tags, it is essential to fully consider the physiological characteristics of animals. Specifically, the size and shape of the animals' ears, as well as the sensitivity of their skin, can directly affect the wearing effect of the ear tags. To ensure the appropriateness of wearing, the size and shape of the ear tags should match the animals' ears, effectively avoiding skin damage or discomfort that may be caused by improper wearing. Researchers clearly pointed out that when applying electronic ear tags to animals such as cattle, sheep, and pigs, their behavioral habits must be fully considered to ensure the stability and reliability of the ear tags[17]. Caja *et al.* specifically pointed out that designs of electronic ear tags are used in sheep under grazing conditions; their design must consider the special structure of sheep ears to ensure the stability of the ear tags during wearing and the comfort of the animals[16].

Traditional ear tag attachment methods often use ear tag pliers to directly clip the ear tag onto the animal's ear. While this method is simple to operate, it can often cause discomfort to the animal and even provoke resistance. In contrast, modern electronic ear tags emphasize the gentleness of installation during their design, typically employing more humane methods such as adhesives or specially designed fastening devices to reduce interference and potential harm to the animals. Bai *et al.* emphasized in their research that when applying electronic ear tags to pig herds, the behavioral habits of pigs must be fully considered to enhance the comfort of wearing the ear tags and the convenience in practical application[18].

Compared to traditional ones, electronic ear tags have made significant advancements in antenna design. The antenna design structure diagram of the electronic ear tag is shown in Figure 2. For instance, the Smartrac Cattle Ear Tag, which uses RAIN RFID technology compliant with the GS1 UHF Gen2 standard, incorporates an embroidered RFID antenna made of wire. This antenna is fixed on a thermoplastic polyurethane (TPU) foil carrier using "Tailored Wire Placement" technology. Unlike conventional etched antennas, this innovative design offers enhanced resistance against structural fractures and interference, thereby improving the tag's reliability in harsh environments. Additionally, it is connected to the chip loop inductively. If the outer antenna is damaged, this configuration allows for the tag and its ID to still be readable over a short distance[7].

3.3. Advancements in manufacturing processes

The introduction of automated production lines is important aspect of the advancement in the manufacturing process of electronic animal tags. Traditional ear tag production largely relied on manual operations, which were inefficient and made it difficult to ensure quality. Modern automated production lines, through precision robotic arms, automatic assembly equipment, and intelligent inspection systems, have achieved full-process automation from raw materials to finished products. This has not only significantly increased production efficiency but also greatly improved the consistency and reliability of product quality. For example, some automated production lines can produce dozens of ear tags per minute, increasing production efficiency several times compared to traditional manual operations.

In the manufacturing field of AEET, the application of quality control technology has made significant progress. Modern quality control processes integrate multiple methods, including visual inspection, laser marking, and RFID testing. The visual inspection system acts as a strict supervisor, monitoring the production process of ear tags in real-time and quickly identifying and eliminating any products that do not meet standards. Laser marking technology, with its precision and durability, ensures the clarity and longevity of the QR codes[19] and numbers on the ear tags. Additionally, the RFID testing system plays a crucial role. It can simulate real-use scenarios to conduct comprehensive and rigorous tests on the read and write performance of the ear tags, ensuring their stability and accuracy in practical applications. Notably, Mora *et al.* developed a new framework that combines detection and tracking systems with RFID systems, successfully improving the accuracy of animal tracking and further ensuring its practical application effects in the breeding field[20].

4. APPLICATION FIELDS OF AEET

4.1. Production management

Through RFID technology, management personnel can obtain real-time specific location information of animals. Mcallister mentioned in his research that electronic identification systems perform excellently in

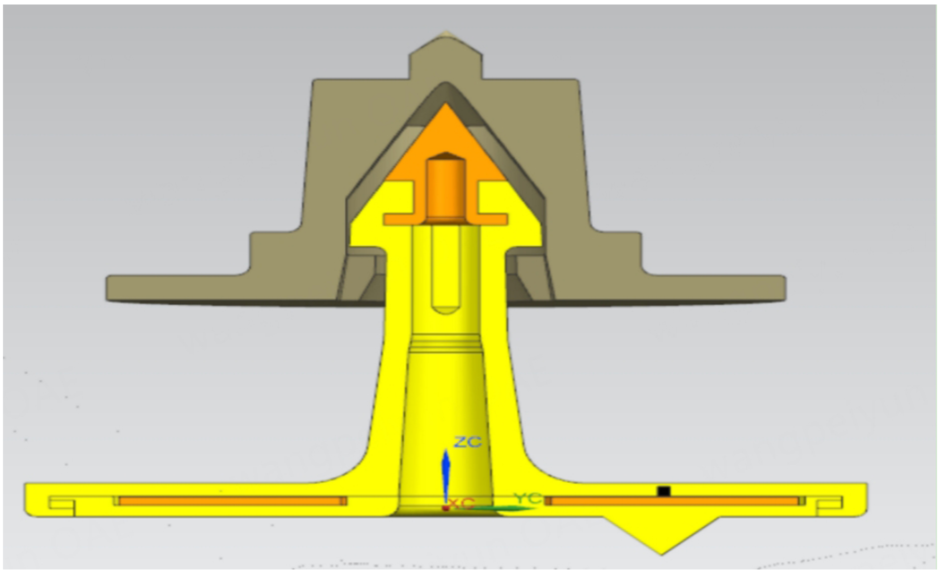

Figure 2. Internal chip diagram of electronic ear tag.

tracking cattle, sheep, and pigs, effectively improving the management efficiency of breeding farms[21]. Carné *et al.* selected kid goats born over a period of three years as experimental subjects to assess the performance of electronic and visual ear tags, and the results showed that electronic ear tags are more reliable in tracking animal locations[22]. Zhang and Zhou pointed out in their research that electronic ear tags can automatically identify target objects through radio frequency signals, and the internal electronic tags, with their excellent durability, can maintain stability for a long time, ensuring the accuracy and continuity of animal identification[23]. Zin *et al.* proposed a cow-location tracking system based on visual analysis for precise tracking. They combine conventional image - processing methods with deep - learning - based object - detection algorithms. Template-matching algorithms or convolutional neural network (CNN) - based image-recognition algorithms are used to process images and identify cow identities by comparing ear-tag data with a database or using trained models. Kalman filters are then applied to predict movement trajectories based on initial positions and motion characteristics. Finally, each cow's location data is incorporated into a global coordinate system, with real-time updates enabling continuous tracking. This system shows strong robustness and accuracy in complex barn environments, effectively tracking cow locations and analyzing behavior patterns[24]. This finding further proves the importance and application value of electronic animal ear tags in livestock management.

At the same time, the research results of Herlin *et al.* also highlighted the key role of digital technology in promoting the progress of animal husbandry, especially the application of electronic ear tags, which significantly improved the production efficiency and refined management level of animal husbandry[25]. Additionally, Panckhurst *et al.* used livestock electronic ear tags with SiRFstarIV chips in their research. These ear tags integrate various sensor modules and are equipped with solar power supply capabilities, enabling real-time management of the movement trajectories and production performance of animals[26]. This multifunctional integrated design significantly enhances the application value and practicality of electronic ear tags. Liu proposed a smart agriculture solution based on blockchain and IoT technology, focusing on achieving precise management of sheep flocks through RFID temperature monitoring and positioning ear tags[3]. This choice of research direction reflects the urgent need for modernization and intelligentization in Chinese animal agriculture.

4.2. Food traceability

The advent of AEET has made it possible to trace the entire chain from the farm source to slaughter and processing, effectively ensuring the safety and quality control standards of food. The study by Caja *et al.* established a full-chain traceability framework for Chinese pork through dual-identification technology (electronic ear tags and subcutaneously implanted RFID chips): piglets are equipped with electronic ear tags and implanted with chips at birth, where the ear tags facilitate daily data collection during breeding (e.g., vaccination records, growth information), while the heat-resistant and tamper-proof implanted chips ensure accurate individual identification even during slaughter and processing. Data is integrated via a cloud-based platform, covering every stage from breeding, transportation, slaughter, to sales, and aligned with national standards such as the "Regulations on Livestock and Poultry Identification and Breeding Archives Management". The research innovatively applies electronic ear tag technology to achieve precise traceability of pork products across all stages from farm breeding to slaughter and processing[27]. At the same time, research by Gosálvez *et al.* demonstrated the application of electronic ear tags in large-scale Iberian pig farms, emphasizing their importance in full traceability[28]. In Ireland, Shanahan *et al.* constructed a global standard-based beef traceability framework, showcasing the potential application of electronic ear tags in the entire chain from farm to slaughterhouse[29]. This framework not only enhances traceability efficiency but also provides strong assurance for food safety.

Many countries abroad have strict regulations and standards for animal identification and traceability systems. For example, the European Union's animal identification legislation requires that all farmed animals must wear electronic ear tags for disease control and food safety traceability[30], which provides strong support for the electronic ear tags and their applications. Madec *et al.* summarized the application of electronic ear tags in different fields and countries in the pig farming industry, pointing out their significant importance for strengthening traceability management in the pig industry[31]. Gao *et al.* discussed the issue of individual identification of livestock, proposing suggestions to strengthen automatic detection, improve traceability systems, and enhance secure identification management,to promote the widespread application of electronic ear tags in animal husbandry[32]. Li mentioned in his research that constructing an efficient animal traceability system based on electronic ear tags has played a positive role in the traceability management of animal products and the prevention and control of major animal diseases[33].

Additionally, electronic ear tags integrated with GPS or RFID technology enable breeders to grasp the location information of animals in real-time and conduct tracking. This feature not only greatly enhances the efficiency of breeding management but also significantly strengthens the traceability of animal products. Research by Maselyne *et al.* further reveals that in the management of animals such as cattle and pigs, the use of different types of ultra-high frequency (UHF) RFID ear tags can achieve precise location and effective tracking of animals[34].

Domestic applications in China are more focused on the breeding segment, especially in large-scale breeding farms. Stankovski *et al.* discussed the application of electronic ear tags in the management of large-scale dairy farms, emphasizing their importance in improving management efficiency and economic benefits[35]. This difference may be related to Chinese breeding patterns and policy orientation. The application of AEET abroad is relatively extensive, covering the entire chain from farm to table. Liang *et al.* demonstrated in their research the full tracking capabilities of electronic ear tags in the breeding, transportation, and slaughter processes of cattle[8]. This kind of chain application helps to improve food safety levels and consumer confidence.

4.3. Breeding management

In genetic research, with the detailed individual information recorded by ear tags, researchers can easily conduct association analyses between genotypes and phenotypes, thereby delving into the specific effects of particular genes on various animal traits. Stärk *et al.* conducted a comparative analysis of the application effects of visual identification and electronic identification devices in pig farming[36]. They found that electronic ear tags showed higher precision and stability in providing individual identification data than visual identification devices. This finding not only emphasizes the importance of electronic ear tags in genetic research but also further enhances the accuracy and reliability of genetic analysis. Using electronic ear tags, we can gain a deeper understanding of the complex relationship between genes and animal traits, providing a more scientific basis for genetic breeding and animal health management. By associating the information recorded by electronic ear tags with an animal's genomic data, researchers can construct detailed and accurate livestock genomic maps, which have far-reaching significance for promoting genetic breeding work. The research by Santamarina *et al.* is a vivid example. They pointed out that in pig farm performance assessment, electronic ear tags demonstrated excellent performance, precisely tracking the growth and development data of each individual pig. These detailed data not only provide valuable genetic information for researchers but also help them optimize breeding programs, improving the production performance and health levels of livestock[37]. Using electronic ear tags, we can further explore the potential of livestock genomes, injecting new vitality into the sustainable development of the livestock industry.

In recent years, Chinese scholars have achieved many results in the scientific research of AEET. Liu *et al.* published a study in "Agricultural Mechanization Research" that introduced the application of smart agriculture based on blockchain and IoT technology, particularly the design and implementation of breeding RFID temperature monitoring and positioning electronic ear tags. The study not only discussed the design of the ear tags but also verified their application effects in free-range sheep flocks through practical testing, proving that the system can accurately measure the body temperature and location of animals, with the characteristics of rapid response and high stability[3].

In practical applications, electronic animal ear tags have been widely adopted and used in many countries and regions. Stärk *et al.* studied the performance of electronic and visual ear tags during the feeding and fattening period of piglets and found that electronic ear tags have a clear advantage in terms of durability and identification accuracy[36]. Additionally, Lee *et al.* conducted a detailed study on growing and fattening pigs in pigpens using BLE and WBLCX antenna systems, which further confirmed the effectiveness and practicality of electronic ear tags in actual breeding environments[38]. It is worth mentioning that Kapun *et al.* documented the application of UHF-RFID systems to record the daily activity patterns of pigs through case studies, demonstrating the diverse applications of electronic ear tags in precision breeding and health management[39]. Applying this technology not only enhances the scientific nature of breeding but also provides strong technical support for market promotion.

These successful practical cases not only demonstrate the advanced and reliable nature of AEET technology but also provide valuable experience and reference for the application of this technology in livestock management in other countries and regions.

4.4. Behavior recognition

AEET not only enables individual animal identification but also collects various data through built-in sensors, greatly enhancing the efficiency and accuracy of scientific research work.

Through the sensors built into the ear tags, researchers can monitor various parameters such as the animals' activity trajectories, activity intensity, and environmental temperature in real-time. Xu *et al.* assessed the application of electronic identification technology in cattle, sheep, and pigs in their study and found that the ear tags could effectively track the animals' movement paths and behavioral performance[40]. Additionally, Kowalski *et al.* studied the performance of electronic and visual ear tags in semi-intensive adult goat herds, and the results indicated that electronic ear tags are more reliable and accurate in tracking animal behavior[41]. By monitoring the frequency of interactions and relative distances between different individuals, researchers can gain a deeper insight into the social structure and complex behavioral patterns of animals. Do Prado Paim *et al.* ingeniously combined thermal imaging technology with electronic ear tags to conduct in-depth research on the behavior of lambs from different genetic groups under changing climatic conditions. Their study not only revealed how genotype and environmental factors jointly influence animal behavior but also provided a new perspective for understanding the complexity of animal social behavior and group dynamics[42]. In the field of environmental science, electronic ear tags are also used to study animals' responses to climate change and environmental pollution. By monitoring the activity trajectories and environmental parameters of animals over the long term, researchers can better understand the interactions between species and their environment within ecosystems[43]. This innovative application not only broadens the research field of electronic ear tags but also brings more possibilities to the study of animal behavior and related fields.

4.5. Disease monitoring

Current electronic ear tags integrate miniature temperature sensors and triaxial accelerometers to collect real-time data on livestock body temperature and movement. The temperature sensor monitors subcutaneous temperature variations through high-frequency sampling (e.g., once per minute), while the accelerometer identifies behavioral patterns such as standing, lying down, and gait by analyzing three-dimensional motion trajectories. After preprocessing via an embedded low-power processor, the data is transmitted to a cloud platform via wireless technologies such as Bluetooth, LoRa, or NB-IoT. AI algorithms then analyze real-time indicators such as abnormal body temperature (e.g., fever) or sudden reductions in activity (pot signaling illness), enabling immediate health alerts, estrus detection, and herd behavior analysis for farms. This system supports precision, intelligent livestock management. Eradus, in his research, clearly pointed out the significant advantages of electronic identification systems in the health monitoring of livestock such as cattle, sheep, and pigs[2]. He emphasized that this system can provide more accurate and timely health information, offering strong support for animal health management. Furthermore, research by Saravanan *et al.* also further validated the effectiveness of electronic ear tags in animal health monitoring. The team found that RFID temperature and location monitoring ear tags based on cloud computing and IoT technology can accurately and quickly measure animal body temperature and location information[44], demonstrating high stability and response speed. The structure diagram of cloud computing and IoT technology is shown in Figure 3. This research outcome not only emphasizes the importance of electronic ear tags in animal disease monitoring but also provides strong evidence for the further application of related technologies. In terms of technical details, Bouazza *et al.* used temperature sensors associated with semi-passive RFID tags to assess the adaptability of various animals under different climatic conditions, indicating that electronic ear tags can not only be used for identity recognition but also combine with other sensor technologies to achieve comprehensive monitoring of animal health and environmental adaptability[45]. Notably, Mar *et al.* proposed a method that integrates deep learning and image processing techniques. During the cow tracking phase, they combined three features: cow position, appearance, and recent features of the cow region. They used the distance between the two centroids of the cow region for association, analyzed appropriate color spaces to extract color moment features, employed a co-occurrence matrix to represent texture features, and utilized a CNN to extract deep features from recent cow images. These elements were all applied to the tracking process to accurately identify and track cows and generate

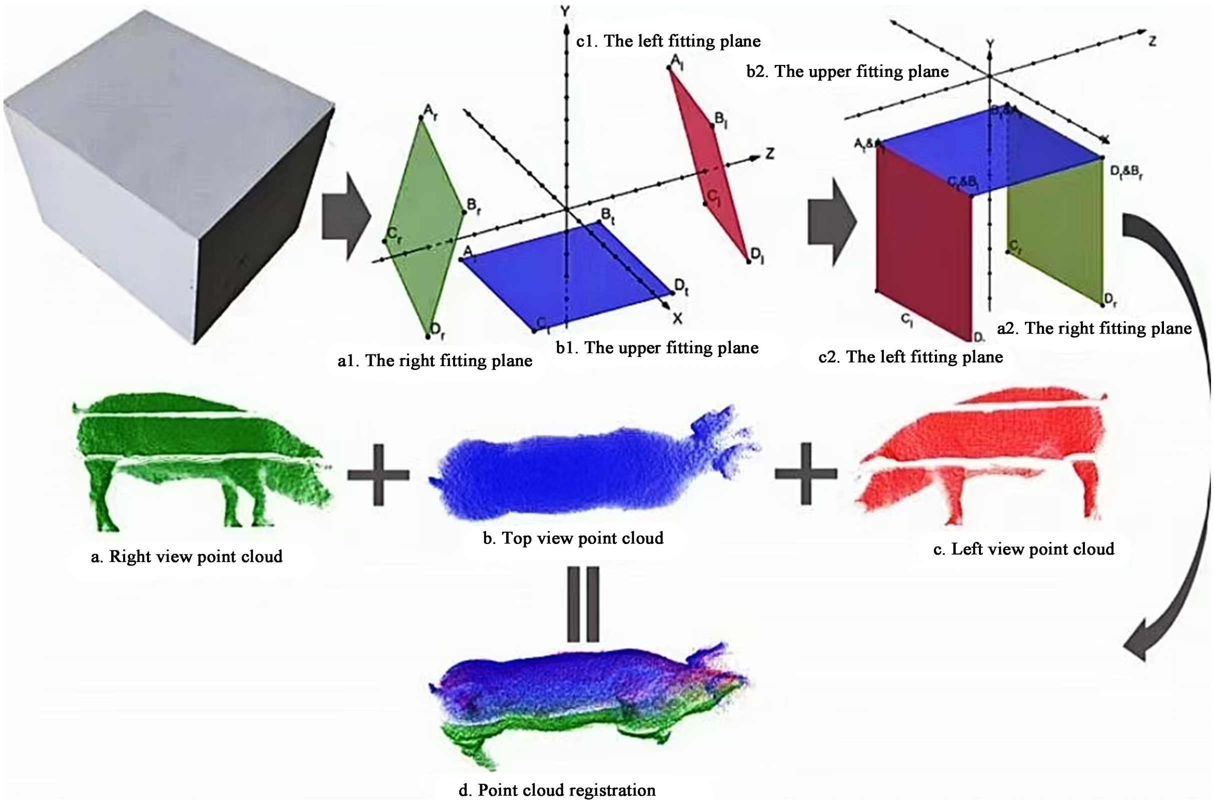

Figure 3. The combination of cloud computing and IoT technology. IoT: Internet of Things.

reliable tracking records. By continuously monitoring behavioral changes in cows, such as their walking activity and the frequency of visits to feed and water stations, early prediction of cow health conditions and disease monitoring can be achieved[46].

The sensors built into AEET can capture physiological data such as body temperature and activity levels in real-time. In a study, Amerson *et al.* ingeniously combined infrared thermography technology with electronic ear tags to conduct an in-depth assessment of the thermal comfort of pigs at 42 days of age under confinement conditions[47]. This innovative method enables continuous, real-time monitoring of the health status of animals. Yang *et al.*, in their research on smart agriculture, designed a temperature and location monitoring ear tag based on blockchain and IoT technology. This ear tag can quickly and accurately measure the body temperature of animals and track their location information in real-time, demonstrating excellent response speed and stability[48]. Xiong *et al.* conducted an in-depth study on the traceability of individual pigs in breeding farms or smallholder farms using electronic ear tags. Their research results showed that electronic ear tags demonstrated excellent performance in tracking the location of animals and monitoring their health status[49]. The application of these advanced technologies not only greatly enhances the scientific nature of animal health management but also makes the management process more efficient and convenient.

The functional requirements of modern electronic ear tags are no longer limited to basic identification but are increasingly demanding the integration of various sensors and communication modules to support more complex and refined management functions. For example, temperature sensors can monitor fluctuations in an animal's body temperature in real-time, providing breeders with timely and accurate data support to help them quickly detect and respond to potential health issues. Karakuş *et al.* pointed out in their research that the application of thermal imaging technology can effectively assess changes in an animal's body temperature under different activity states, which is extremely important for early disease warning and precise management[50].

By constructing an integrated big data platform, the animal producers can consolidate and analyze animal health data from multiple breeding farms, thereby quickly capturing the initial signs of epidemics and taking timely and effective control measures accordingly. Taking research by Bhole *et al.* as an example, they successfully combined thermal imaging technology with electronic ear tags to conduct individual monitoring of Holstein cows based on their coat patterns, providing a solid scientific basis for disease prevention and control[51]. Furthermore, research by Edwards *et al.* under farm grazing conditions also fully demonstrated the excellent performance of electronic ear tags. They found that the application of electronic ear tags in sheep flocks significantly improved the efficiency of disease monitoring and epidemic early warning, providing strong protection for the healthy development of the breeding industry[52].

After an outbreak, quickly tracing the source of the epidemic is crucial for controlling the spread of the disease. AEETs, with their ability to record animal identity information and track their movements, enable full-chain traceability from the farm to slaughter and processing. A study by Santamarina *et al.* is a prime example, demonstrating that electronic ear tags play a pivotal role in the breeding and slaughtering process of pigs, accurately tracing the origin and movement of animals, and providing strong support for the effective control of disease transmission[37]. Additionally, research by Hammer *et al.* further underscores the advantages of electronic ear tags in tracing the sources of outbreaks. By comparing different UHF RFID ear tags, they verified the application effects of these ear tags in detecting both cattle and pigs, significantly enhancing the efficiency and accuracy of tracing the sources of outbreaks[17]. In another study, Chen *et al.* adopted a wireless sensor network data transmission architecture, transforming the passive monitoring function of traditional RFID ear tags, improving the durability and high recognition rate of electronic ear tags, and significantly enhancing the efficiency and accuracy of quarantine work[53].

With the continuous advancement of technology, the application of AEET in the field of disease prevention and control is making breakthroughs. The research by Zhang *et al.* has brought us the testing methods for UHF RFID luminescent electronic ear tags, an innovative approach that opens up a new path for the rapid search and precise positioning of individual animals, greatly enhancing the efficiency and accuracy of disease prevention and control[54]. At the same time, research by Mahfuz *et al.* also reveals the huge potential of ICT-based livestock electronic ear tags in promoting the modernization of livestock management[55]. Research by Groher *et al.* delves into the widespread application of digital technology in animal husbandry, particularly emphasizing the significant advantages of electronic ear tags in monitoring animal health and production performance[56]. These electronic ear tags not only ensure the quality and safety of livestock products but also significantly improve the management level of the livestock industry, laying a solid foundation for the sustainable development of the industry.

It is worth mentioning that with the continuous innovation of the IoT and information technology, the design and application of AEET are experiencing unprecedented innovation. Wang *et al.* developed a breeding RFID temperature monitoring and positioning electronic ear tag based on smart agriculture information technology. This ear tag ingeniously integrates multiple key modules such as a temperature sensor, Proportional-Integral-Derivative (PID) controller, and antenna, achieving real-time and precise monitoring of animal body temperature and location[57]. The introduction of this technology not only greatly improves the level of intelligent management in animal husbandry but also opens up new avenues for animal health management and disease prevention and control.

5. CHALLENGES AND PROSPECTS OF AEET APPLICATIONS

5.1. Technical deficiency needs improving

The performance of existing electronic ear tags under extreme weather conditions needs to be improved. Karakus *et al.* pointed out in their research that the performance of electronic ear tags is affected when used under grazing conditions[58]. Therefore, enhancing the stability and durability of ear tags under various climatic conditions remains a problem that needs to be addressed urgently. Although UHF RFID ear tags have made breakthroughs in communication distance, signal interference and attenuation are still serious issues in complex environments, such as breeding farms. The compatibility of the devices is also an important issue. Electronic ear tags produced by different manufacturers may use different standards and protocols, which poses challenges for device interoperability. Adrion *et al.*'s study indicates that compatibility issues with different UHF RFID ear tags when detecting cattle and pigs simultaneously need to be further addressed[7].

5.2. Challenges of data management

The challenges of AEET in data management mainly lie in collection, storage, and processing. Through RFID technology, a large amount of information about animals is collected, including identification, health status, production performance, and more. The volume and complexity of these data present significant challenges in efficiently managing and utilizing them. Karakus *et al.* pointed out that while electronic ear tags perform well under grazing conditions in Turkey, there is still a need for further optimization in data management[58]. In practical applications, the real-time updating and accuracy of data are particularly important. Groher *et al.* also mentioned that the application of digital technology in animal husbandry requires a robust data management platform to ensure the reliability and timeliness of data[56].

5.3. Cost issues

The issue of cost is also an important factor that restricts the widespread application of electronic ear tags. Although electronic ear tags have significant advantages in improving management efficiency and animal welfare, their high cost still deters many farmers. Zhang *et al.* mentioned that the testing methods and judgment criteria for electronic ear tags need to be further improved to reduce costs and increase the popularity rate[59].

Electronic ear tags are mostly powered by batteries, which have a limited lifespan and are inconvenient to replace. Richard proposed a solar panel-based electronic ear tag design in his research[60], aiming to improve energy efficiency and extend the service life. However, achieving efficient energy management while ensuring the miniaturization of ear tags remains a technical challenge. Despite continuous technological advancements, the cost of manufacturing electronic ear tags remains high, especially when integrating multiple high-performance sensors and chips. In the study by Ait-Saidi *et al.*, the implementation of electronic identification for performance recording in dairy and meat sheep was evaluated, emphasizing the importance of conducting effective monitoring under economically viable conditions[10]. The key to promoting electronic ear tags is to further reduce costs while ensuring performance. Kaniyamattam *et al.* have compared electronic ear tags with traditional ones in dairy farms. They found that electronic ear tags are more cost-effective on large-scale ranches. Animal identification systems collect detailed data on cattle growth, reproduction, health, and milk production. Ranchers can use this data to understand each cow's condition, thus optimizing feeding, reproduction planning, and disease prevention. This improves resource efficiency and cuts costs. For instance, analyzing data can determine the best feed formula to prevent waste and reduce disease occurrence and treatment costs based on health data[61].

5.4. Challenges in privacy protection

Electronic ear tags can record detailed information about animals, and if this information is misused or leaked, it could have adverse effects on animal welfare and agricultural production. Bergqvist *et al.* pointed out that traditional electronic ear tags are prone to wear and fall off during use, making it impossible to recognize animal information, thereby affecting the effectiveness of privacy protection[62]. In practical applications, ensuring the security and privacy of data is an urgent problem to be solved. Research by Elliott indicates that the acceptance of national animal identification systems by farmers is influenced by privacy protection measures[63]. Study by Felmer *et al.* also emphasizes the need to pay attention to privacy protection in the application of current emerging technologies in animal identification and traceability[64]. The standardization and interoperability of electronic ear tags are the foundations for animal traceability and management on a global scale. There are existing differences in electronic ear tag standards, with various frequencies and technical standards adopted by different countries and regions, leading to compatibility issues between devices. Burose *et al.* studied fixed RFID antenna systems for pig identification, emphasizing the importance of standardization[65]. Promoting international standardization cooperation and establishing unified technologies is an important direction for future development. With the popularization of electronic ear tags, data security and privacy protection issues are becoming increasingly prominent. The animal health and production data recorded by electronic ear tags need to be properly protected to prevent data breaches and misuse. Ensuring data security and privacy protection during data collection, transmission, and storage is an issue that cannot be overlooked in electronic ear tag technology.

5.5. Future development trends

With the continuous advancement of technology, electronic animal ear tags will usher in more technological innovations and application expansions in the future.

The future of AEET is set to become more intelligent, not only possessing basic identification functions but also integrating a greater array of sensors and data processing capabilities. Smart agriculture applications based on blockchain and IoT technology can achieve the integration of multifunctional modules, such as temperature sensors and received signal strength indicator (RSSI) positioning[48]. Symeonaki *et al.* proposed an ontology-based IoT middleware approach for IoT integration in smart livestock production. This approach, centered on distributed IoT middleware, aims to meet the unique needs of livestock production by building a responsive, adaptable service-oriented integrated farm management system. Specifically, the middleware integrates a flexible ontology-based structure for context awareness and reasoning, effectively managing, processing, and sharing large amounts of heterogeneous data from livestock facilities. In a case study on smart thermal environment control in pig facilities, sensors collected environmental data, which was preprocessed by the IoT middleware and then stored and analyzed using cloud computing resources. Combined with context-aware technology, this enabled real-time monitoring and precise control of the thermal environment in pig facilities, showcasing excellent computational performance as well as the ontology's coherence, consistency, and efficiency[66]. This enhancement in intelligence allows ear tags to monitor the health status, activity trajectories, and production performance of animals in real-time, thereby improving the precision and scientific level of breeding management. As wireless communication technology continues to evolve, the communication capabilities of AEET will also be significantly enhanced. Existing low-frequency and high-frequency RFID technologies will be upgraded with UHF and even higher frequency RFID technologies, greatly improving the reading distance and data transmission speed of the ear tags. Furthermore, the introduction of 5G technology will provide electronic ear tags with higher bandwidth and lower latency, enabling them to support a wider range of application scenarios.

Traditional electronic ear tags typically rely on battery power; however, batteries have a limited lifespan and require periodic replacement. Future electronic ear tags may adopt more advanced energy supply methods, such as solar charging and energy harvesting technologies. Panckhurst mentioned in his research that electronic ear tags integrated with solar panels can achieve continuous power supply, thereby extending the service life of the ear tags[26]. This innovation will make electronic ear tags more convenient and economical in practical applications.

As consumer demands for food safety and traceability continue to grow, AEET will play an increasingly important role in the traceability across the entire industry chain. Zambelis *et al.* pointed out that the application of electronic ear tag technology in modern dairy management is not only related to the breeding and epidemic prevention of dairy cows but also plays a significant role in disease treatment and product tracking[67]. In the future, electronic ear tags will be combined with blockchain technology to achieve full-chain traceability from breeding to slaughter and then to sales, ensuring food safety and quality.

Precision livestock farming is a crucial direction for the future development of the livestock industry, and AEETs will be key tools to achieve this goal. By monitoring the health status and production performance of animals in real-time, electronic ear tags can provide breeding enterprises with accurate data support, thereby optimizing breeding management plans and enhancing production efficiency and economic benefits. With the acceleration of globalization, AEET will play an increasingly important role in cross-regional and international contexts. By adopting unified standards and technical specifications, electronic ear tags from different countries and regions can achieve interconnectivity, thereby enhancing the overall management level of the global livestock industry.

6. CONCLUSION

Through the comprehensive analysis of multiple documents, this article reveals the development process and significant role of AEET in modern animal husbandry. As an advanced identification technology, AEETs have been widely applied in various animal farming and have achieved remarkable application outcomes. In the future, electronic ear tags are expected to further develop in the following aspects: (1) strengthen field experiments across different regions and environments to verify the universality and stability of electronic ear tags; (2) explore new materials and technologies which are low-cost and highly durable to reduce the application barriers; (3) integrate IoT and blockchain technologies to enhance the data transmission efficiency and security of electronic ear tags, and to build a more comprehensive animal traceability and management system.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Peng, W.; Liu, Z.

Conceptualization, supervision: Cai, J.

Conceptualization, supervision, draft improvement: Zhao, Y.

Availability of data and materials

Not applicable.

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Conflicts of interest

Cai, J. is the General Manager of Anhui Hatai Intelligent Technology Co., Ltd. The other authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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