Liu *et al. Animal Diseases* (2024) 4:48
https://doi.org/10.1186/s44149-024-00151-w

REVIEW

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Epidemiological characteristics and prevention and control strategies for *Eimeria* spp. in sheep and goats in China: a systematic review

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Abstract

Sheep and goat coccidiosis has a worldwide distribution and is an important disease on lambing farms. Infection with multiple *Eimeria* species can lead to severe intestinal damage in sheep/goats and economic losses on farms. Disease is a serious constraint to the healthy development of small ruminant farming. Studies published on PubMed, CNKI, VIP, Wanfang and the resulting references of selected studies were included. Risk factors affecting prevalence were analyzed and stratified by geographic location and climatic variables, age, sex, feeding model, season, sample year, breeds and environment. The total prevalence of coccidia in sheep and goats reached more than 60% in most regions, in which the dominant species in sheep were mainly *E. parva*, *E. ovinoidalis*, and *E. parva* and *E. ahsata*. East China had the lowest prevalence of coccidia infection in sheep (43.24%), and the dominant species were different from those in the other regions, mainly *E. bakuensis* and *E. gonzalezi*. Southwestern China and Central China had slightly less than 40.0% goat coccidia infection, and the dominant species in goats were mainly *E. arloingi*, *E. aligevi*, *E. hirci* and *E. ninakohlyakimovae*. Sheep/goats of different ages can be infected with coccidiosis, but lambs between 1 and 3 months of age are more susceptible to the disease. When lambs become infected, the pathogen spreads rapidly throughout the herd. Spring, summer and autumn are the seasons with a high incidence of this disease. Environmental pollution may be a significant factor in the development of coccidiosis in sheep raised in large-scale housing. This study provides a comprehensive overview of the species, morphology and geographic distribution of *Eimeria* species in sheep and goats, summary prevalence in different regions of China, risk factors affecting prevalence, and prevention and control strategies.

Keywords Coccidiosis, *Eimeria*, Epidemiology, Geographical distribution, China, Sheep and goats

Introduction

China is a traditional agricultural country, and animal husbandry is an important part of it (Hao 2017). Sheep and goat raising is an important industry that dominates the economic income of herdsmen. In China, mutton is the fourth most consumed meat, and meat products and goat milk are indispensable and important foods (Wei 2015; Pan and Li 2022). Furthermore, goat milk, wool (fleece), sheep casings, and sheep skins also hold a significant position in the economy. Owing to the gradual

Handling editor: Shuai Wang.

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increase in consumer demand in recent years, sheep and goat breeding has become more large-scale and intensive. By the end of 2022, the population of sheep and goats had reached 326 million (146 million goats, 179 million sheep) in China (Zhao 2022). However, high-density breeding conditions have led to an increase in the frequency of infectious diseases and parasitic diseases (Yi 2022). Among of them, intestinal parasitic diseases are one of the key factors restricting the healthy development of the sheep industry, which can lead to slow growth and development of sheep/goats, reduce the reproductive performance and quality of livestock products, cause chronic wasting diseases, and even cause death. (Zheng 2019; Saratsis et al. 2011).

Intestinal parasitic pathogens in sheep and goats commonly include coccidia, *Cryptosporidium*, *Blastocystis* spp., and Microsporidia, among which coccidia have the highest infection rate (Zheng 2019). Coccidia of sheep (goats) belong to the Apicomplexa, Sporozoea, Coccidia, Eucoccidiida, Eimeriina, and Eimeriidae genera of *Eimeria* and parasitically infect intestinal mucosal epithelial cells with a high degree of host specificity, which is particularly common in lactating lambs and 2–4 weeks after weaning (Wang et al. 2010; Macrelli et al. 2019). Coccidiosis is one of the most important parasitic diseases affecting the economy of small ruminants. Fitzgerald (1980) estimated that the annual economic loss caused by coccidiosis in sheep is US$140 million (Wang et al. 2010). It was not until the 1960s that coccidia were recognized as causing disease in the United Kingdom (Andrews 2013a). Coccidia can invade and destroy the host's intestinal epithelial cells, causing digestive disorders in the body. Most young and adult sheep are subclinically infected, meaning that although they are infected with *Eimeria*, they do not show clinical symptoms. Lambs are the most susceptible, with clinical manifestations of diarrhea, emaciation, growth retardation, and, in severe cases, acute enteritis leading to death (Khodakaram-Tafti and Hashemnia 2017). Although deaths of young and adult sheep due to coccidia infection are very rare, subclinical infection can lead to growth retardation and reduced reproductive performance and yields of mutton, goat milk, and wool (velvet), causing serious economic losses in the sheep industry and severely hindering the healthy development of the sheep and goat breeding industry (Macrelli et al. 2019; Keeton and Navarre 2018a).

Since Moussu and Marotel (1901) first described a type of Eimeria in sheep (*Eimeria faurei*), a total of 17 *Eimeria* species of sheep have been identified (Wang 1990; Peng et al. 1994). There are 13 species recognized by most scholars: *Eimeria ahsata* (*E. ahsata*), *E. bakuensis*, *E. crandallis*, *E. faurei*, *E. gonzalezi*, *E. granulosa*, *E. intricata*, *E. marsica*, *E. weybridgensis*, *E. puncatata*, *E. gilruthi*, *E. ovinoidalis* and *E. pallida* (Peng et al. 1994; Zhao et al. 2012). Among these coccidia species, *E. ovinoidalis*, *E. bakuensis*, *E. crandallis* and *E. ahsata* are considered pathogenic to sheep, with *E. ovinoidalis* being the most pathogenic (Saratsis et al. 2011). Since Marotel (1905) first described a type of *Eimeria* in goats (*E. arloingi*), a total of 16 *Eimeria* species in goats have been identified. Currently, 13 *Eimeria* species of goats are recognized by most scholars (Wang 1990; Peng et al. 1994; Abo-Shehada and Abo-Farieha 2003): *E. kocharli*, *E. ninakohlyakimovae*, *E. arloingi*, *E. pallida*, *E. jolchijevi*, *E. hirci*, *E. caprovina*, *E. alijevi*, *E. punctata*, *E. caprina*, *E. apsheronica*, *E. christenseni*, and *E. gilruthi* (Kheirandish et al. 2014). *E. christenseni*, *E. arloingi*, *E. ninakohliyakimova* and *E. caprina* are considered pathogenic to goats, with *E. ninakohliyakimov*a being the most pathogenic (Saratsis et al. 2011; Andrews 2013b). Although researchers have found a high degree of host specificity in coccidia through extensive cross-infection testing, with cattle, sheep, and goats each having specific *Eimeria* species infections, *E. pallida* and *E. punctata* are still common to both sheep and goat coccidia.

Eimeria spp. is a direct developmental type that does not require an intermediate host. The life cycle can be divided into two main stages, with schizogony and gametogony as the endogenous phase and sporogony as the exogenous phase (Fig. 1) (Saratsis et al. 2011). In general, oocysts shed in feces undergo sporogony (a meiotic process) in the external environment, a process requiring oxygen, taking approximately 48 h. The sporulated oocysts contain four sporocysts, each containing two sporozoites. Upon ingestion by sheep/goats, oocysts excyst within the intestinal lumen. This process is aided by trypsin, bile, and CO_2. The released sporozoites penetrate the villous epithelial cells. Sporozoites of some species develop within cells at the site of penetration. Sporozoites of other species are transported to other sites, such as the crypt epithelium, where they undergo development. Within the host cells, sporozoites undergo asexual reproduction (schizogony or merogony), in which nuclear division is followed by cytoplasmic differentiation, resulting in merozoites that break free and penetrate other host cells. These may carry out several more merogonic generations. Sexual reproduction or gametophytes follow the last merogonic cycle. Merozoites enter host cells and develop into either male (microgametocyte) or female (macrogametocyte) forms. The microgametocyte gives rise to many microgametes that exit, seek, and penetrate (fertilize) the macrogametes that then develop into unsporulated oocysts, shedding with feces. Prepatent periods may generally range from

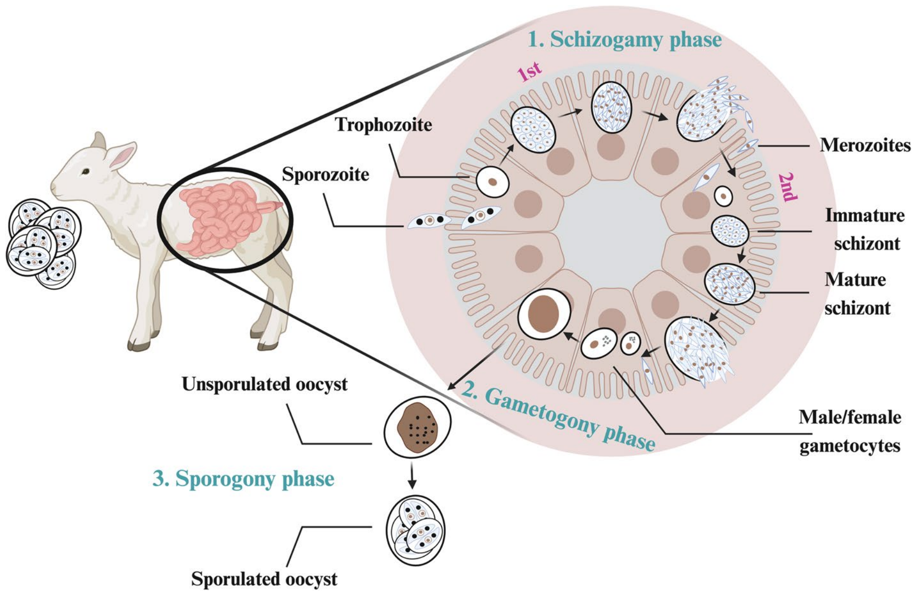

Fig. 1 Life cycle of *Eimeria* species of sheep and goats (created with BioRender.com)

11–17 d post infection, and the maximum oocyst output ranges from 13–15 d post infection (Cheng 2023).

Coccidia are highly host-, tissue- and site-specific and are differentiated and identified on the basis of the host, parasitic site and sporulated oocyst morphology. The morphology of sporulated oocysts mainly includes oocysts (size and shape), oocyst walls (number, color, smooth or rough), sporocysts (size and shape), polar caps, micropores (size and shape), polar granules (size and morphology), oocyst residual bodies (size and morphology), stied bodies and substied bodies (size and morphology), sporocystic residual bodies and refractile bodies. In addition to the morphological characteristics of coccidia, the average length and width of the oocysts (shape index) constitute one of the main bases for identifying coccidia species.

This article summarizes the coccidia detection results of sheep/goats from 23 provinces/cities across the country over the past ten years and analyzes the coccidia infection situation from the perspective of *Eimeria* species distribution, region, breeds, sex, feeding mode and dominant species to provide information for the prevention and control of coccidia in sheep. In addition, this article reviews the species, geographical distribution, morphological analysis, molecular biology detection methods and risk factors for *Eimeria* in sheep and goats, providing basic information for a comprehensive understanding of the epidemiology of *Eimeria* in sheep and goats.

Literature search and selection

A thorough literature search was conducted to identify relevant studies published in scientific journals, conference proceedings, and reports. The inclusion criteria focused on epidemiological studies that investigated the occurrence and characteristics of *Eimeria* spp. infections in Caprinae populations in China. We searched three databases (the PubMed, China National Knowledge internet (CNKI), VIP and WanFang databases). In PubMed, we used the MeSH index to determine the following subject terms: "Goats/Sheep", "*Eimeria*" and "China". In the MeSH terms, the free words obtained for goats were "Goats", "*Capra*", and "*Capras*"; the free words obtained for sheep were "*Ovis*", "Dall Sheep", "*Ovis dalli*", and "Sheep, Dall". The free words obtained by *Eimeria* were "Eimeria", "Coccidia" and "Coccidias". China's free words were "People's Republic of China" and "Mainland China". Finally, the search strategy we established was as follows: ("*Eimeria*" [Mesh] OR *Eimerias* OR Coccidia OR Coccidias) AND ("Goats" [Mesh] OR Goat OR *Capra* OR *Capras*) AND ("China" [Mesh] OR People's Republic of China OR Mainland China), ("*Eimeria*" [Mesh] OR *Eimerias* OR Coccidia OR Coccidias) AND ("Sheep" [Mesh] OR *Ovis* OR *Dall* Sheep OR *Ovis dalli*) AND ("China" [Mesh] OR People's Republic of China OR Mainland China). For other domestic *Eimeria* coccidia, refer to the above search strategy.

In the three Chinese databases (CNKI, VIP and WanFang), the search queries we chose were "Goat/Sheep" and "*Eimeria*" in Chinese, and we conducted a final search on February 21, 2024. Eliminate irrelevant articles through document titles and abstracts.

Eimeria species and geographical distribution

Eimeria coccidiosis is a self-limiting disease caused by protozoa belonging to Apicomplexa, Conoidasida (Conoidasida), Eucoccidiorida (Eucoccidiorida), Eimeriorina (Eimeriorina), Eimeriidae (Eimeriidae), and *Eimeria* (*Eimeria*), with a high degree of host specificity. To comprehensively understand the coccidia species of sheep (*Ovis aries*) and goats (*Capra hircus*) and their distributions in different regions of China, we reviewed the literature and collected references published thus far in China.

Eimeria species infection in sheep (*Ovis aries*)

There are a total of 17 *Eimeria* species of sheep distributed in 22 provinces and cities in China, including 3 new species (*E. oodeus*, *E. pachmenia* and *E. guyuanensis*) reported from China (Wang 1990; Odden et al. 2018; Huang et al. 2022a). Among them, *E. ahsata*, *E. bakuensis*, *E. crandallis*, *E. faueri*, *E. granulosa*, *E. intricata*, *E. pallida* and *E. parva* are widely distributed. *E. gilruthi* and *E. guyuanensis* have been reported in only Gansu (Huang et al. 2022b) and Ningxia (Xiao 1992), respectively. *E. oodeus* has been reported in only Qinghai (Li et al. 2013a) and Xinjiang (Hu and Yan 1991). *E. punctata* has only been reported in Henan, Shaanxi, and Yunnan. Our laboratory reported a total of 12 species of Hu sheep in Heilongjiang, among which *E. gonzalezi*, *E. marsica*, *E. weybridgensis* and *E. ovinoidalis* were newly discovered (Wang 2022). Among the 22 provinces listed, the provinces with the most reported *Eimeria* species were Henan, Shaanxi, Yunnan and Xinjiang (13 species), followed by Liaoning, Heilongjiang and Tibet (12 species), Fujian Province had the least reported species, and only *E. faurei* was detected.

Eimeria species infection in goats (*Capra hircus*)

Capra hircus belongs to Bovidae, Caprinae, Caprini, and *Capra*, with a total of 13 *Eimeria* species from goats distributed in 23 provinces and cities (Wei 2015; Huang et al. 2017). Because of the morphological similarity of some *Eimeria* coccidia oocysts in goats and sheep, they were previously regarded as the same species, and their species names were used interchangeably between goats and sheep. Recently, through a large number of oocyst cross-transmission tests, increasing evidence has shown that goat coccidia have host specificity; parasitized goats and sheep, some coccidia are morphologically similar to different species, and different species names are used to avoid confusion.

A total of 13 species of goat coccidia have been identified, among which *E. alilijevi*, *E. absheronae*, *E. arloingi*, *E. christenseni*, *E. caprovina*, *E. hirci*, *E. jolchijevi* and *E. ninokohlyakimovae* are widely distributed. *E. shunyiensis* has only been reported in Beijing (Wang and Su 1989). Our laboratory identified 5 *Eimeria* species in Hainan black goats, namely, *E. alilijevi*, *E. caprovina*, *E. hirci*, *E. pallida* and *E. punctata*, which filled the gap in the identification of Hainan sheep coccidia species (Jian et al. 2021). Among the 23 provinces listed, the provinces with the most reported coccidia species were Anhui, Henan, Jiangsu and Tibet (12 species), followed by Fujian, Guizhou, Shaanxi, Yunnan and Taiwan (11 species).

Morphological analysis

Morphological identification is based on descriptions in the literature (Berto et al. 2014; Zhang et al. 1758; Hanson et al. 1957). Morphological data combined with developmental studies of oocysts are crucial for determining the species of coccidia. The morphological characteristics evaluated were length (L), width (W), range and ratio (L/W), micropyle (M), polar cap (PC), polar granule (PG), and oocyst residue body (ORB); the sporocyst characteristics were L, W, L/W, stieda body (SB) and sporocyst residue body (SRB) (Table S1) (Zhang et al. 1758). Line drawings of a sporulated oocyst were constructed with Adobe Illustrator CC 2020 software (https://www.adobe.com) (Figs. 2 and 3).

Identification of *Eimeria* spp. in sheep and goats

The primary approaches for detecting coccidia include morphology, molecular biology, and immunology. Nonetheless, morphological and molecular biology assays are the predominant methods employed for *Eimeria* spp. in sheep and goats.

The conventional morphological detection approach relies on fecal flotation techniques, wherein the morphology of the oocysts is discerned through microscopic examination. This method is cost-effective and straightforward to execute and is extensively used for field detection (Cheng et al. 2022). However, owing to the high degree of similarity in the morphology of the oocysts of *Eimeria* spp., morphological methods make distinguishing between the different species difficult. Therefore, its application is limited to preliminary screening of coccidia populations or large-scale epidemiological studies.

With the development of molecular techniques, PCR (polymerase chain reaction) and qPCR (quantitative PCR) have become more sensitive and specific detection methods. PCR technology is able to differentiate accurately between different coccidia species by amplifying coccidia-specific DNA sequences. qPCR not only detects the presence of coccidia but also allows for the

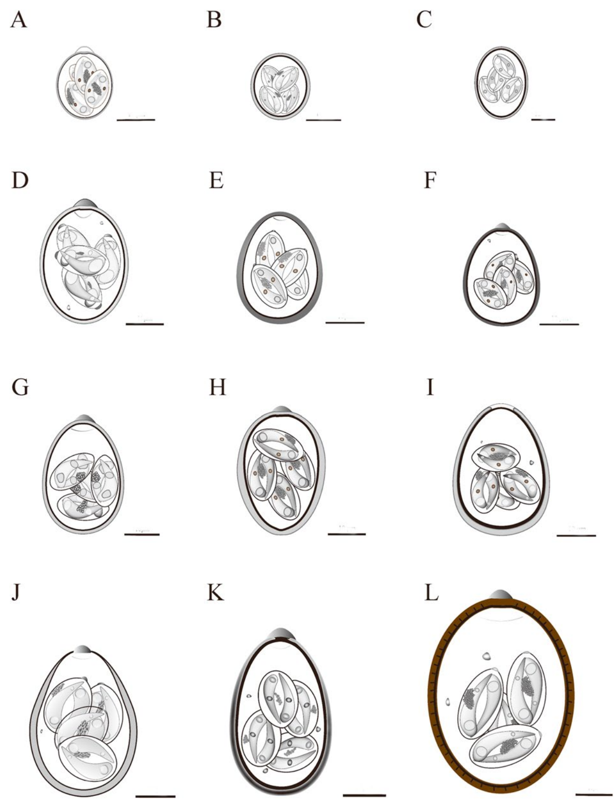

Fig. 2 Line drawing of *Eimeria* oocysts in sheep. Bar means 10 μm. **A**. *E. marsica*; **B**. *E. parva*; **C**. *E. pallida*; **D**. *E. gonzalezi*; **E**. *E. ovinoidalis*; **F**. *E. crandallis*; **G**. *E. weybridgensis*; **H**. *E. granulosa*; **I**. *E. faurei*; **J**. *E. bakuensis*; **K**. *E. ahsata*; **L**. *E. intricate*

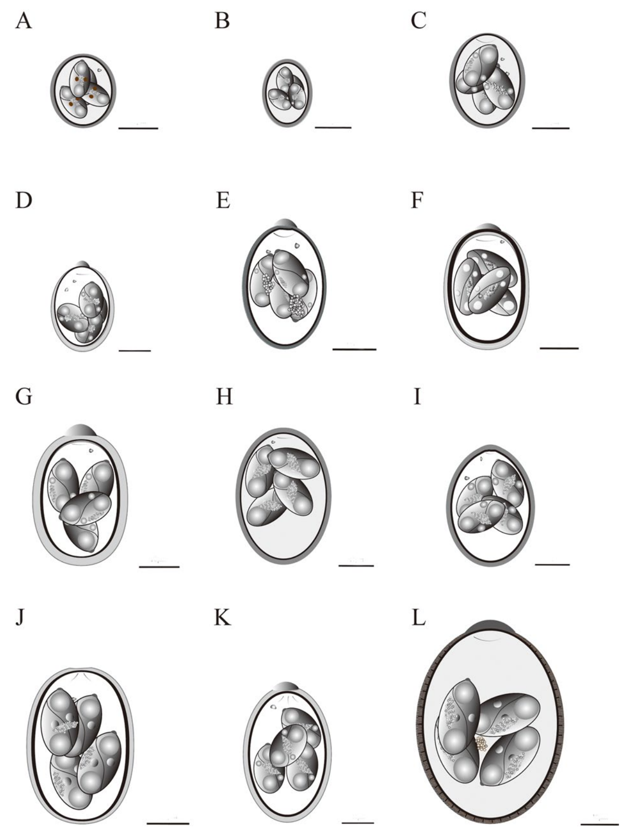

Fig. 3 Line drawing of *Eimeria* oocysts in goats. Bar means 10 μm. **A**. *E. alijevi*; **B**. *E. pallida*; **C**. *E. ninakohlyakimovae*; **D**. *E. hirci*; **E**. *E. punctata*; **F**. *E. arloingi*; **G**. *E. jolchijevi*; **H**. *E. caprovina*; **I**. *E. apsheronica*; **J**. *E. caprina*; **K**. *E. christenseni*; **L**. *E. kocharli*

quantitative analysis of the pathogen load. The high sensitivity and specificity of these techniques have led to their widespread use in laboratory diagnostics and research.

Several genetic loci, such as 18S rDNA, ITS-1, ITS-2, and COI, have been applied in the molecular characterization of *Eimeria* in chickens, rabbits, turkeys, and wildlife, but little is known about these molecular markers of *Eimeria* in goats and sheep. Berriatua developed a DNA probe assay to identify the presence of coccidia associated with *E. ovinoidalis* and *E. crandallis* (Berriatua et al. 1995). The method was able to detect the DNA present in approximately 1500 oocysts, and to increase the sensitivity of the assay, a PCR method was developed that uses specific primers to clone repetitive sequences to accurately detect fewer than 10 oocysts of sheep. Rongchang Yang developed and validated a qPCR method targeting the 18S rRNA gene and examined the prevalence of infection and oocyst concentrations of coccidia in fecal samples from lambs during three sampling periods (weaning, postweaning, and preslaughter) to determine the presence or absence of *Eimeria* species (Yang et al. 2014). Verma amplified the gene fragments of *E. ninakohlyakimovae*, *E. christenseni* and *E. alijevi* via 18S rDNA and ITS-1 genes and analyzed them for molecular characterization (Verma et al. 2017).

Shijie Li established a SYBR Green real-time fluorescence qPCR assay for the rapid detection of *Eimeria* spp. in ovis (Li 2022). The sensitivity of the assay was 34 copies/μL, and it could effectively amplify $34–3.4\times10^8$ copies/μL standard plasmids of the target gene. Liang established PCR assays for the detection of *E. arloingi*, *E. christenseni* and *E. ninakohlyakimovae*; the susceptibility of the method was 197, 234 and 22.7 copies, respectively, and there was no cross-reactivity with other parasitic protozoa or helminths of the digestive tract of goats (Liang et al. 2022). Phylogenetic analysis based on ITS-1 and ITS-2 was not effective in distinguishing *Eimeria* species from sheep and goats, whereas the COI locus could effectively distinguish *Eimeria* species from goats and cattle but was ineffective in distinguishing *Eimeria* species from sheep and goats (Tran et al. 2022). Zhengrong Fan established a PCR method for the detection of *E. parva* and *E. ovinoidalis* with a minimum detection level of 0.1 ng (Fan 2022). Xingyue Zi developed a multiplex PCR method for *E. crandallis* and *Cryptosporidium* with good specificity

Table 1 Progress of some studies on the prevalence and dominance of spp. in sheep and goats in different regions of China

Regions	Breeds	Infection rate (100%)	*Eimeria* spp. (Dominant spp.)	Reference
Shaanxi	Goat	92.7% (51/55)	*E. arloingi*, *E. ninakohlyakimovae*, *E. alijevi*, *E. caprovina*, *E. alijevi*, *E. christenseni*, *E. hirci*, *E. jolchijevi*	Zhang FF, et al., 2013
Hubei	Goat	72.6% (485/668)	*E. arloingi*, *E. alijevi*, *E. christenseni*, *E. caprovina*, *E. caprina*, *E. hirci*, *E. jolchijevi*, *E. ninakohlyakimovae*	Xi MW, et al., 2017
Xizang	Goat	81.2% (211/260)	*E. alijevi*, *E. pallida*, *E. arloingi*, *E. christenseni*, *E. caprovina*, *E. caprina*, *E. hirci*, *E. jolchijevi*, *E. ninakohlyakimovae*, *E. apsheronica*, *E. punctata*, *E. kocharli*	Jiang WD, et al., 2017
Shanghai	Goat	80.0% (96/120)	*E. christenseni*, *E. caprina*, *E. apsheronica*, *E. ninakohlyakimovae*, *E. jolchijevi*, *E. hirci*, *E. alijevi*, *E. arloingi*	Yu XX, et al., 2017
Sichuan	Goat	98.3% (456/464)	*E. arloingi*, *E. jolchijevi*, *E. christenseni*, *E. alijevi*, *E. caprovina*, *E. hirci*, *E. caprina*, *E. ninakohlyakimovae*, *E. apsheronica*	Hao GY, 2016
Jiangsu	Goat	63.6% (197/310)	*E. arloingi*, *E. christenseni*, *E. ninakohlyakimovae*, *E. caprina*, *E. alijevi*	Cao SY, 2021
Hunan	Goat	72.6% (111/150)	*E. arloingi*, *E. alijevi*, *E. apsheronica*, *E. jolchijevi*, *E. christenseni*	Tian MT, et al., 2021
Hainan	Goat	98.9% (86/87)	*E. alijevi*, *E. pallida*, *E. caprina*, *E. hirci*, *E. christenseni*	Liu LK, et al., 2021
Henan	Goat	95.2% (62/63)	*E. arloingi*, *E. alijevi*, *E. christenseni*, *E. hirci*, *E. caprina*, *E. pallida*, *E. intricate*, *E. ninakohlyakimovae*, *E. jolchijevi*	Li MJ, et al., 2012
Shaanxi	Goat	92.4% (724/784)	*E. arloingi*, *E. apsheronica*, *E. alijevi*, *E. christenseni*, *E. hirci*, *E. caprina*, *E. jolchijevi*, *E. ninakohlyakimovae*, *E. caprovina*	Liu LK, et al., 2021
Hainan	Goat	75% (75/100)	*E. pallida*, *E. alijevi*, *E. caprina*, *E. hirci*, *E. caprovina*	Jian YC, et al., 2021
Henna	Sheep	95.7% (155/162)	*E. bakuensis*, *E. marsica*, *E. gonzalezi*, *E. granulose*, *E. intricate*, *E. parva*	Zhu D, et al., 2012
Henan	Sheep	96.1% (933/971)	*E. bakuensis*, *E. ahsata*, *E. parva*, *E. faurei*, *E. ovinoidalis*, *E. pallida*, *E. gonzalezi*, *E. granulose*, *E. intricate*, *E. marsica*, *E. crandallis*, *E. weybridgensis*	Zhang FF, et al., 2013
Qinghai	Sheep	70.8% (68/96)	*E. parva*, *E. ovinoidalis*, *E. crandallis*, *E. weybridgensis*, *E. bakuensis*, *E. ahsata*, *E. faurei*, *E. pallida*, *E. gonzalezi*, *E. granulose*, *E. intricate*, *E. marsica*	Li CH, et al., 2013a
Xinjiang	Sheep	50.9% (59/116)	*E. ahsata*, *E. bakuensis*, *E. gonzalezi*, *E. parva*, *E. granulose*, *E. intricate*, *E. marsica*, *E. weybridgensis*	Jiang WD, et al., 2017
Inner Mongolia	Sheep	86.9% (287/330)	*E. granulose*, *E. crandallis*, *E. ovinoidalis*, *E. ahsata*, *E. bakuensis*, *E. weybridgensis*, *E. faurei*, *E. intricate*, *E. gonzalezi*	Wang ZM, 2022
Henan	Sheep	87.56% (373/426)	*E. ovinoidalis*, *E. pallida*, *E. bakuensis*, *E. ahsata*, *E. parva*, *E. faurei*, *E. gonzalezi*, *E. granulose*, *E. intricate*, *E. marsica*, *E. crandallis*, *E. weybridgensis*	Gong PH, 2022
Henan	Sheep	71.5% (123/172)	*E. ovinoidalis*, *E. parva*, *E. ahsata*, *E. bakuensis*, *E. pallida*, *E. faurei*, *E. marsica*, *E. granulose*, *E. intricate*, *E. crandallis*, *E. weybridgensis*	Lu CY, 2022
Jiangsu	Sheep	91.13% (113/124)	*E. bakuensis*, *E. parva*, *E. ovinoidalis*, *E. weybridgensis*, *E. pallida*, *E. faurei*, *E. crandallis*, *E. ahsata*, *E. intricate*	Fan ZR, 2022
Xizang	Sheep	79.19% (491/620)	*E. parva*, *E. pallida*, *E. ovinoidalis*, *E. ahsata*, *E. bakuensis*, *E. gonzalezi*, *E. weybridgensis*, *E. faurei*, *E. crandallis*, *E. ahsata*, *E. intricate*, *E. granulose*, *E. marsica*, *E. punctata*	Chang YK, 2018

and sensitivity, and the minimum DNA detection limits were 0.1 ng/μL DNA for *E. crandallis* and 1 ng/μL DNA for *Cryptosporidium* (Zi 2023).

In summary, although morphological and molecular techniques are currently the mainstays of coccidia detection, new technologies and methods (e.g., immunological assays and genome sequencing techniques) are expected to provide additional help in the early diagnosis and control of coccidiosis in the future as the demand for testing continues to grow.

Prevalence of *Eimeria* species in different regions of China

The literature related to the epidemiological investigations of sheep and goats *Eimeria* spp. in China was collected and organized by the researcher, and some of the research progress on the prevalence and dominance of Eimeria spp. in different regions of China is shown in Table 1, with no further citations in the text.

Analysis of the results of the survey in each region revealed that the average *Eimeria* spp. infection rates of sheep and goats in each region of China were 43.2%–93.8% and 35.8%–91.5%, respectively. All *Eimeria* species of sheep and goats are distributed in different geographic regions of China, and the dominant species are *E. bakuensis*, *E. ahsata*, and *E. parva* of sheep and *E. arloingi*, *E. ninakohlyakimovae* and *E. alijevi* of goats (Table 1 and Table S2, S3). We counted articles related to epidemiological investigations on sheep coccidia from 2010-2024, excluded studies with only positive rates and no work on speciation, and mapped the total prevalence and dominant species of *Eimeria coccidia* in sheep and goats in different regions of China based on the final

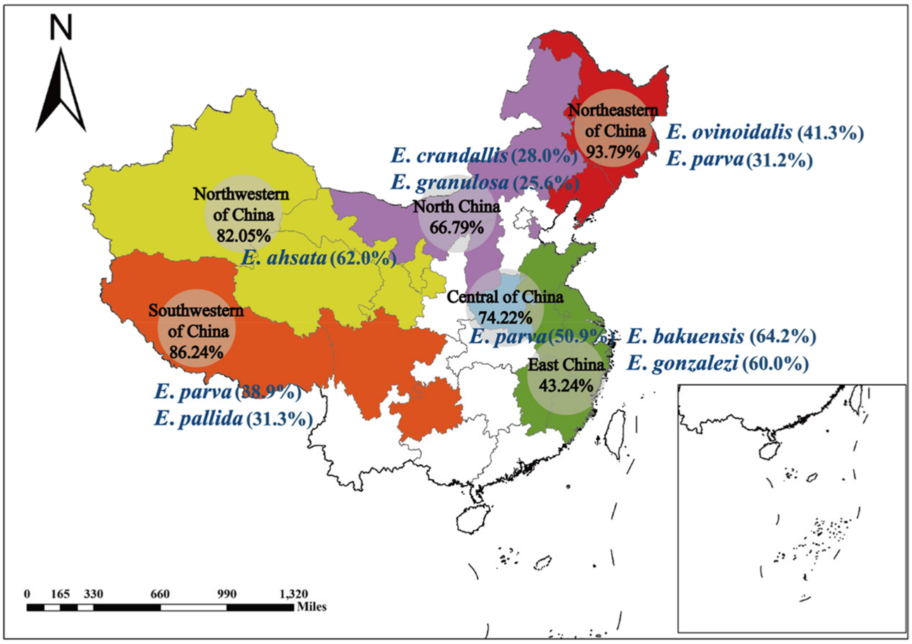

Fig. 4 Pooled prevalence and dominant *Eimeria* species of sheep in different regions of China. China is divided into seven regions according to its seven natural geographic regions: Northeast China (NE), North China (N), Central China (C), East China (E), South China (S), Southwest China (SW) and Northwest China (NW)

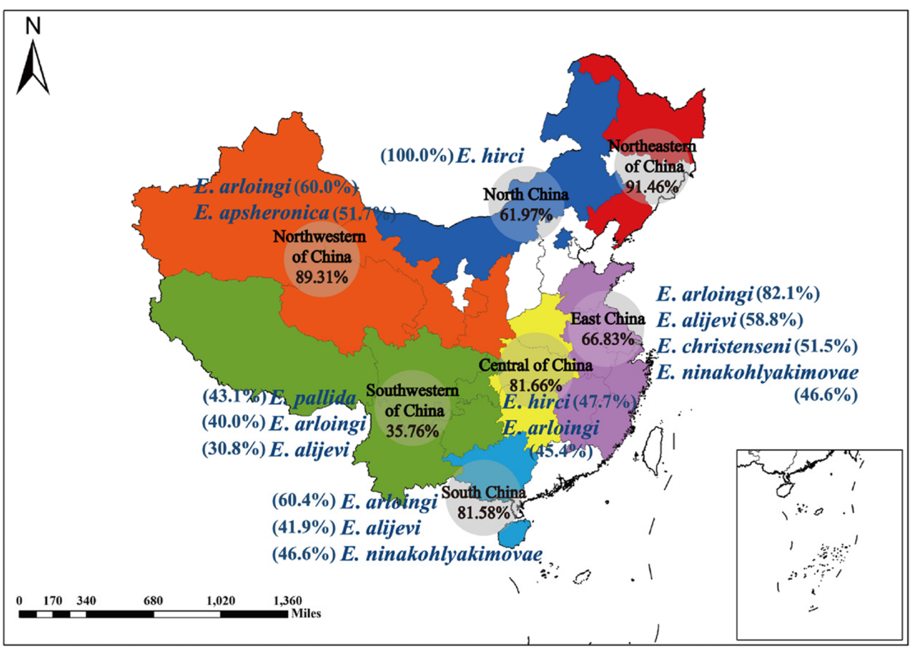

Fig. 5 Pooled prevalence and dominant *Eimeria* species in goats in different regions of China. China is divided into seven regions according to its seven natural geographic regions: Northeast China (NE), North China (N), Central China (C), East China (E), South China (S), Southwest China (SW) and Northwest China (NW)

statistics (Figs. 4 and 5). The blanks of the maps may have relevant streaming data that were not included in our study.

Sheep

Since the literature did not include reports on *Eimeria* species in sheep in South China, we counted the results for only six regions (Fig. 4, Table S2). We found that the total infection rate, the number of *Eimeria* species identified and the dominant species varied significantly among different regions: the highest infection rate was found in Northeast China (93.8%, 438/467), with a total of 12 *Eimeria* species identified in sheep, namely, *E. ahsata*, *E. bakuensis*, *E. crandallis*, *E. faurei*, *E. gonzalezi*, *E. granulosa*, *E. intricate*, *E. marsica*, *E. weybridgensis*, *E. ovinoidalis*, *E. pallida*, and *E. parva,* and the dominant species were *E. ovinoidalis* (41.3%, 83/201) and *E. parva* (31.3%, 63/201). The Southwest region had the next highest total coccidia infection rate (86.2%, 2119/2457), with 12 *Eimeria* species of sheep identified, which was consistent with those identified in Northeast China, with the dominant species being *E. parva* (38.9%, 328/843) and *E. pallida* (31.3%, 194/620).

The overall prevalence of *Eimeria* species in sheep in Northwest China was 82.1% (11,114/13,545), which was slightly lower than that in Southwest China. In this region, 12 *Eimeria* species were also identified, with the dominant species, unlike in Northeast China and Southwest China, being *E. ahsata* (62.0%, 803/1296). Infection rates vary widely among regions in Central China, with an overall sheep coccidia infection rate of approximately 74.2% (1155/2770). A total of 13 *Eimeria* species were identified in sheep: *E. ahsata*, *E. bakuensis*, *E. crandallis*, *E. faurei*, *E. gonzalezi*, *E. granulosa*, *E. intricate*, *E. marsica*, *E. weybridgensis*, *E. puncatata*, *E. ovinoidalis*, *E. pallida*, and *E. parva*. The dominant species was *E. parva* (50.9%, 1155/2770). A total of 9 *Eimeria* species were identified in North China: *E. ahsata*, *E. bakuensis*, *E. crandallis*, *E. faurei*, *E. granulosa*, *E. intricate*, *E. weybridgensis*, *E. ovinoidalis*, and *E. parva*. The dominant species were *E. crandallis* (28.0%, 35/125) and *E. granulosa* (25.6%, 32/125), with an overall prevalence rate of 66.8% (1458/2183).

The region of East China includes Shandong, Anhui, Jiangsu, Shanghai, Zhejiang, Jiangxi, Fujian and Taiwan provinces. Epidemiological examinations of sheep *Eimeria* spp. have only been conducted in Shandong, Jiangsu, since 2010, with a total of 1,346 samples collected. Twelve *Eimeria* species were identified, which is consistent with Northeast China, Southwest China, and Southwest China. The dominant species were *E. bakuensis* (64.2%, 226/352), *E. gonzalezi* (60.0%, 18/30) and *E. parva* (49.7%, 175/352), with an overall prevalence of 43.2% (582/1346), which was the lowest infection rate in China.

Goats

Consistent with the results for sheep, the pooled prevalence of *Eimeria* species in goats was also highest in Northeast China (91.5%, 75/82). The results are biased due to the small sample size. There are no articles available in the area for identifying *Eimeria* species, so the results (Fig. 5, Table S3) do not present the dominant insect species in the area. The Northwest region had the next highest overall prevalence (89.3%, 5071/5678), with a total of 10 *Eimeria* species identified, namely, *E. jolchijevi*, *E. hirci*, *E. arloingi*, *E. christenseni*, *E. apsheronica*, *E. caprovina*, *E. punctata*, *E. caprina*, *E. ninakohlyakimovae*, and *E. alijevi*, and the dominant species were *E. arloingi* (60.0%, 229/382) and *E. apsheronica* (51.7%, 151/292). The total prevalence in Central China was 81.7% (3980/4874), and a total of 12 *Eimeria* species were identified, including *E. kocharli* and *E. pallida*, in addition to the 10 *Eimeria* species identified in northwestern China.

The total prevalence in central of China was 81.7% (3980/4874), and a total of 12 *Eimeria* species were identified, including *E. kocharli* and *E. pallida*, in addition to the 10 *Eimeria* spp. identified in northwestern China. The total prevalence in East China was 66.8% (3683/5511), and 10 species were identified in the region, namely, *E. jolchijevi*, *E. hirci*, *E. arloingi*, *E. christenseni*, *E. apsheronica*, *E. caprovina*, *E. caprina*, *E. ninakohlyakimovae*, *E. alijevi* and *E. pallida*, with the dominant species *E. arloingi* (82.1%,1153/1404), *E. alijevi* (58.8%, 837/1424), *E. christenseni* (58.8%, 733/1424) and *E. ninakohlyakimovae* (46.6%, 690/1482).

The total prevalence in North China was slightly lower than that in East China, where nine *Eimeria* species were identified, namely, *E. jolchijevi*, *E. hirci*, *E. christenseni*, *E. apsheronica*, *E. caprovina*, *E. caprina*, *E. ninakohlyakimovae*, *E. alijevi* and *E. pallida*, with the dominant species being *E. hirci* (100.0%, 36/36). The total sample size in the region is relatively small and is only representative of the prevalence in a given area. The total prevalence in Southwest China was the lowest in China (35.8%, 4923/13678). Twelve *Eimeria* species were identified in this region, and the *Eimeria* species were consistent with Central China, with the dominant species being *E. pallida* (43.1%, 135/313), *E. arloingi* (82.1%, 1153/1404) and *E. alijevi* (30.8%, 925/2999). The total prevalence of infection was 91.6% in Northeast China, a region where the literature reports no work on identification species and where the dominant species was not counted for the time being.

Risk factors influencing the prevalence of *coccidia*

Coccidiosis caused by *Eimeria* spp. is one of the most common intestinal diseases in domestic animals (Ruiz et al. 2006). Whether there is a clinical infection, or the livestock is in a subclinical state, it can cause economic losses (Zhao et al. 2012; Keeton and Navarre 2018b). Various risk factors that contribute to the transmission and spread of *Eimeria* spp. in Caprinae populations have been identified. These factors include intensive farming practices, overcrowding, poor sanitation, age, sex and climatic conditions conducive to oocyst survival and development (Carrau et al. 2018). The following is a review of the factors influencing the prevalence of coccida:

Geographic location and climatic variables

In warm and humid environments, coccidia are highly sporulated and easily transmitted, resulting in a high rate of infection in sheep. Therefore, in southern coastal areas, lake areas, riversides, and rainy seasons, sheep and goats are susceptible to coccidia infection. Diao et al. (2022), according to a meta-analysis of geographical subgroups, reported that the prevalence was highest when the longitude was 80–105° (84.6%), and the same was true for latitudes ranging from 30–35° (80.5%), precipitation > 800–2000 mm (79.8%), annual average temperature ranging from 5–10°C (84.8%), humidity ranging from 80–100% (95.7%), and altitudes above 1500–5000 m (81.2%). The highest point estimate was in northwestern China, where the prevalence of *Eimeria* spp. varies with precipitation level, and *Eimeria* spp. infection is more prevalent in places with moderate temperature and humidity (Diao et al. 2022). In 15 grazing-reared sheep flocks in Fujian Province surveyed in 2015, the average infection rate was 90.8%, and seven *Eimeria* species were found: *E. parva*, *E. ninakohlyakimovae*, *E. hirci*, *E. caprina*, *E. arlongi*, *E. christenseni*, and *E. apsheronica* (L L, J B, W SH, Z SZ, L ZS, L S,, et al. 2015).

Zheng Ling collected 935 sheep fecal samples from six provinces, and the total infection rate of coccidia was 81.1% (Zheng 2019). The highest infection rate was found in the central region, which may be due to the high rainfall and humid air in the central region. The northeast region has low rainfall but low temperature and humid air, and its coccidia infection rate is also relatively high. The lower infection rate in the southwest and northwest regions may be due to the warm climate and low precipitation, which is not conducive to the reproduction of coccidia. The lower infection rates in the southwestern and northwestern regions may be due to the warm climate and low precipitation, which are not favorable for coccidia reproduction.

The variations in sampling volume across different regions may have resulted in deviations in the findings. However, these results serve as a reminder to pay attention to the prevention and control of sheep coccidia in Northeast China and goat coccidia in East China. It is important to strengthen the prevention and control of sheep coccidia infection, while other regions should consider their climate and geographical conditions and strengthen the detection of coccidia in the environment and sheep flocks. Targeted prevention and control measures should also be implemented.

Age

Livestock of different ages are susceptible to coccidia, and young animals are highly infectious and severely harmful. In terms of age, Diao et al. (2022) reported that the estimated prevalence of the main factors influencing overall age (89.9%) was greater in goats ≤ 1 year than in those > 1 year of age (82.2%). Lin et al. investigated the infection of *Eimeria* in Nantong and found that the infection intensity of lambs aged 1-3 months was significantly higher than at other ages, and found that infection rates in young and adult sheep are relatively low, but infection rates in lambs reaching up to 100.0% (Diao et al. 2022). Gong et al. (2021) analyzed the prevalence of coccidia in different pig stages (suckling piglets, weaning pigs, growing pigs, finishing pigs), and the results revealed that the prevalence of coccidia in finishing pigs was highest (21.1%), that in suckling piglets (19.9%), that in growing pigs (12.0%), and that in weaning pigs (11.6%) (Gong et al. 2021). According to reports, the coccidia prevalence in cattle of all age groups varies greatly and affects mainly calves reported that, after weaning (2–12 months of age), calves had the highest prevalence (37.1%) (Makau et al. 2017; Ekawasti et al. 2019; Li et al. 2021). Scholars from Shanghai, Anhui, Northeast China, Inner Mongolia, Jiangsu, Guangzhou and Henan investigated coccidia infection in cows and cattle and reported that calves under 12 months of age were susceptible, whereas the infection rates in cattle under 1 month of age and those over 24 months of age were low. The severity of rabbit coccidia infection decreases with age, and young rabbits at 4–5 months of age have weak resistance to coccidia (An 2013).

Gender

In a meta-analysis study, female goats (89.9%, 800/897) had a greater prevalence of *Eimeria* infection than male goats did (70.7%, 120/211), and the point estimates of coccidia prevalence were slightly greater in sows (21.1%, 1075/4449) than in gender boars (21.1%, 386/1565), but the differences were not significant ($P < 0.05$) (Diao et al. 2022; Gong et al. 2021). Yang (2022) reported that sex had no significant effect on coccidia infection in dairy goats. In our pooled prevalence rate, ewes (83.19%, 945/1136) had a higher prevalence than rams did (79.66%, 278/349) in both sheep and goats.

Feeding modes

There are two main modes of animal husbandry in China: intensive farming and free-range farming. Different feeding patterns also affect coccidia infection in domestic

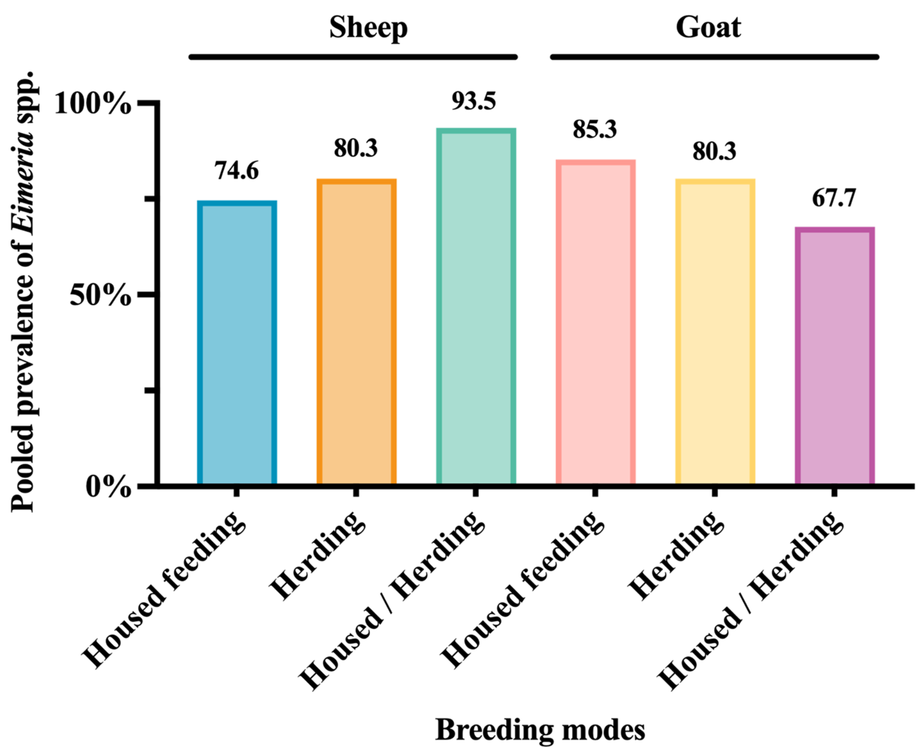

Fig. 6 Pooled infection rates of *Eimeria* spp. in goats and sheep with different breeding modes

animals. According to Lin, goats kept under house-feeding conditions had an average infection rate of 46.0%, whereas those kept under grazing conditions had an average infection rate of 90.8%. Wang (Wang 2017) investigated the intestinal parasite infection of sheep in Anhui and its surrounding areas and reported that the infection rate of coccidia was 22.6%, and the infection rate of free-range sheep (Chizhou) was significantly higher than that of noncaptive sheep, as was the result of Qiao (Qiao et al. 2009) and Li et al. (Li et al. 2013b). In 2022, Diao analyzed the total infection rate of coccidia in goats under different feeding patterns in China (Diao et al. 2022), and the estimated prevalence among free-range goats (79.4%, 2295/2940) was higher than that among intensively farmed goats (77.4%, 6,326/8,521).

The results of our laboratory's epidemiologic investigation of coccidia in sheep revealed that, during herding (83.5%, 1953/2338), the coccidia infection rate is higher than that in housed sheep (71.2%, 3254/4568). A greater percentage of the goats were housed (92.8%, 1114/1200) than free-range (84.9%, 214/623). Our pooled results (Fig. 6, Table S4) revealed that sheep had the lowest total coccidia infection rate in the housing group (74.6%, 4151/5565) and the highest infection rate in the housing/herding group (93.5%, 446/477). Interestingly, the results among goats were completely opposite to those among sheep, with the lowest infection rate in the housed/herding feeding group (67.7%, 536/792) and the highest infection rate in the housed-feeding group (85.3%, 6679/7832). The above results may be related to the small sample size, deworming, regional variability, and inability to fully represent the total epidemic trend. Sheep are housed at high densities because of their docile character, whereas goats are housed at relatively low densities because of their active and aggressive nature. The data are not representative of actual infections without reference to the context in which the drugs were administered. In addition, in sheep, the infection rate of coccidia was lower than that of herding, and the opposite was true in goats, which suggests that we should strengthen the cleanliness, hygiene and dryness and ventilation of the goat house and its environment in the process of coccidia prevention and control in sheep. In contrast, goats have a higher infection rate of coccidia in housed conditions, which may be due to the biological characteristics or behavioral habits of goats that cause them to ingest oocysts more readily in housed environments, for example, more intense exploratory habits, which may result in easier access to contaminated floors and feed.

This difference also suggests the need to adopt specific strategies for different farming modes when preventing and controlling coccidiosis in different species of livestock, e.g., for housed goats, we need to strengthen the cleaning and disinfection of pens as well as the management of individual health, whereas for sheep, we need to pay attention to the prevention and control of coccidiosis even under housed conditions.

Season

Coccidia has a certain seasonality, is more prevalent in rainy, hot and humid environments, and usually occurs from May to September every year, with the highest incidence occurring from June to July. Infection by *Eimeria* spp. in goats is considered to have no obvious seasonality (Hao 2017). The infection rate of *Eimeria* was significantly higher in summer and autumn than in winter investigated and analyzed the infection situation of sheep coccidia on large-scale sheep farms in alpine areas and reported that the infection rate was high from May–September (Wang 2022; Ma et al. 2018). These findings indicate that coccidia infection in sheep is related to local climatic conditions. In the rainy season from May to September, the humidity of the enclosure is relatively high, which is favorable for the development of oocysts, and the sheep are relatively likely to be infected with coccidia. It is recommended that the sheep house be well ventilated, clean and regularly disinfected in spring, summer and fall to reduce the rate of coccidia infection. Li et al. conducted a one-year follow-up survey on two sheep farms in Henan Province, collected 644 fecal samples, and reported that the parasitic infection rates of sheep in spring, summer, fall and winter were 98.5%, 99.4%, 100.0% and 94.0%, respectively (Li et al. 2013b). The infection rate of coccidia was the highest among the four seasons and was as high as 100.0% in autumn, whereas the infection rate of coccidia was the lowest in winter, at 92.3%.

Many studies did not provide details of the sampling month, which also had a certain impact on the analysis of the seasons. When investigating coccidiosis, researchers should clarify the sampling month because such details can be used to analyze the effects of season and other climatic factors on goat coccidiosis (Diao et al. 2022).

Sample year

In 2006, China's Ministry of Agriculture issued the "Parasitic Disease Control Plan (2006-2016)", which was subsequently extended to 2021 to further strengthen the prevention and control of parasites. In the sampling year subgroup, the pooled prevalence before 2006 (83.7%, 2238/2794) was higher than that in 2006 or later (75.3%, 10,823/20728), the prevalence of *Eimeria* spp. in goats in China also showed a downward trend (Diao et al. 2022), the pooled prevalence before 2000 (57.9%, 1130/1875) was higher than that from 2000–2015 (37.2%, 5707/15956) and 2015 (25.0%, 1152/4509), the prevalence of *Eimeria* spp. in bovines in China also showed a downward trend (Li et al. 2021), and the pooled prevalence of pig coccidia infection detected in 2000 or earlier (32.6%, 1540/3756) was higher ($P < 0.05$) than that obtained in the other tested periods (Gong et al. 2021).

No meta-analysis has been conducted on the influence of sampling year on coccidia prevalence in other domestic animals (rabbits and sheep), so the relationship between sampling year and coccidia prevalence cannot be determined.

Goat and sheep breeds

There are currently 12 recognized species of *Eimeria* that originate from sheep. However, it is important to note that no single species of coccidia affects all sheep, indicating that there are species differences in *Eimeria* infection between goats and sheep in different regions. These differences may be related to the breed of sheep and their location. Additionally, the geographical environment and climatic conditions, such as rainfall, may also play a role. Additionally, various factors, such as feed and medication, can also affect it (Jing et al. 2019; Zheng et al. 2018).

According to Wang Zhanming's epidemiological survey, the infection rates of Australian dairy sheep, Dukhan hybrid sheep, Mongolian sheep, Landreth sheep, and Dexel sheep were 98.4% (2251/255), 94.9% (280/295), 87.0% (287/330), 84.4% (27/32), and 75.0% (39/52), respectively (Wang 2022). Among them, Mongolian sheep were infected with nine species of *Eimeria*, with *E. crandallis* and *E. granulose* being the dominant species. A total of 12 species of Dukhan hybrid sheep were found, with *E. ovinoidalis* being the dominant insect species. Among the Australian dairy sheep, seven species were found, with *E. ovinoidalis* and *E. intricata* being the dominant insect species. The Dexel sheep included a total of seven species, with *E. ovinoidalis* being the dominant species. The lettuce sheep included five species, with *E. ahsata*, *E. pallida*, and *E. ovinoidalis* being the dominant insect species. The Hu sheep included a total of 12 species, with *E. ovinoidalis* being the dominant insect species. Researchers investigated the prevalence of *E. marsica* and *E. bakuensis* infections in large-tailed Han sheep (a Chinese native sheep breed distributed in the Central Plains of China) in Jiaxian County, Henan Province and identified five species of *Eimeria* in Hotan sheep and eight species of *Eimeria* in Cele black sheep. However, *E. ahsata* was the dominant species, while *E. parva* and *E. bakuensis* infections were also common.

We conducted a pooled analysis of the total infection rate of *Eimeria* species in different goats and sheep breeds and reported that the general infection rate was high in different goat breeds: the highest infection rates of sheep coccidia were found in Kaulidai sheep (96.5%, 328/340), Weining sheep (96.3%, 437/454), large-tailed

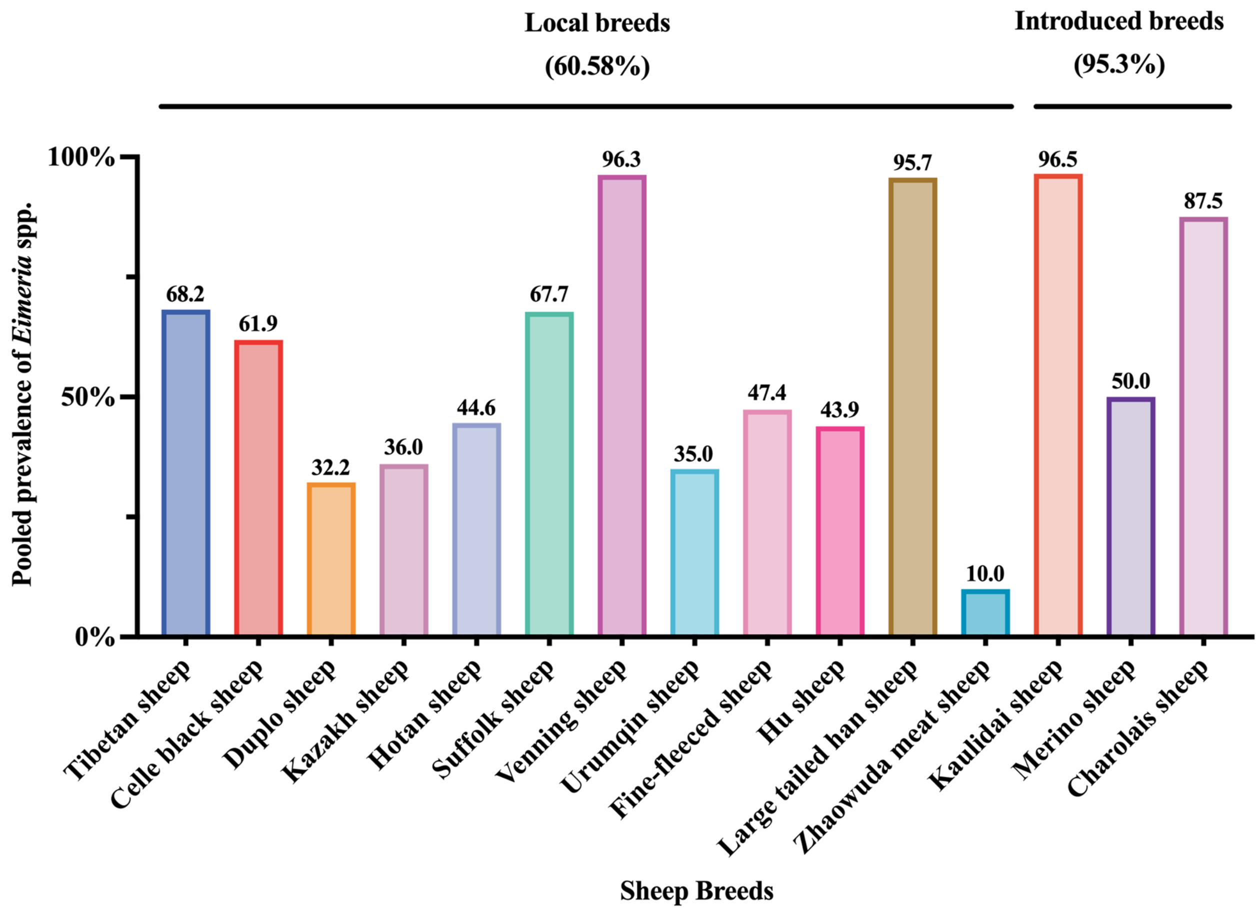

Fig. 7 Pooled prevalence of *Eimeria* spp. in different sheep breeds in China

Han sheep (95.7%, 203/210) and Charolais sheep (87.5%, 14/16). Tibetan Sheep, Celle Black Sheep, Suffolk Sheep and Merino Sheep have infection rates of 50.0%–70.0%. Overall, the total prevalence of *Eimeria* coccidia in localbred sheep (60.6%) was lower than that in induced breeds (95.3%), with the lowest prevalence in Zhaowuda meat sheep (10.0%) (Fig. 7, Table S5). Among the goats, Youzhou Wu Goat, Tuggenburg Goat and Alpine Goat had the highest infection rates (100.0%), followed by Yaoshan White Goat, Jining Gray Goat, Tibetan Goat, Locust Goat, Dairy Goat and Boer Goat (80.0%-95.0%). The black goat had the lowest infection rate (17.0%, 1530/8979) (Fig. 8, Table S5). These findings indicate that there is a difference in parasite (*Eimeria* coccidia) resistance between goat breeds, and the results can provide a basic basis for future research on resistance to intestinal parasitic diseases, especially coccidiosis.

The above results may be related to the following reasons: (1) Local breed sheep may have developed a certain degree of genetic resistance to the locally prevalent species of *Eimeria* coccidiosis over a long period of natural selection and adaptation to the local environment, providing better resistance to the locally prevalent species of *Eimeria* coccidiosis. (2) Locally bred sheep may be better adapted to local feeding environments and conditions, including climate, feed resources, etc., which may influence the prevalence of coccidiosis. (3) Local breeds of sheep are usually associated with feeding management practices that match their growing environment, such as grazing regimes, pen hygiene, and deworming frequency and methods, which may be more in line with best practices for the prevention and control of coccidiosis, thus effectively reducing infection rates. (4) The immune systems of different breeds of animals may differ in their response to the same pathogen, and local breeds of sheep may have stronger natural or acquired immunity against *Eimeria* coccidia infection.

In addition, local breeds of Weining sheep (96.3%) and Big-tailed Han sheep (95.68%) have the highest infection rates of *Eimeria* coccidia, which may be related to their local climate and geographic environment, as well as their feeding methods and management conditions, and should be strengthened to prevent and control *Eimeria* coccidia in the region as well as the need to improve the feeding environment, strengthen feeding management, implement a scientific system of disease prevention and control, rationally use anti-coccidia drugs, and enhance awareness of disease prevention and control among farmers and other aspects. Again, there is no background information on the use of drugs, and it is possible that some breeding farms focus on deworming in the above data and that the infection rate and worm load of coccidia will be greatly reduced after regular deworming.

Environment

Currently, there are numerous studies on coccidia infection in sheep across various regions of the country. However, reports on the impact of environmental pollution on coccidia are lacking. Gong collected environmental samples such as feed residues and feces from the entrance (Gong 2022), exit, aisle and bed areas of sheep barns in Henan Province; examined the detection of environmental parasites in sheep barns in different seasons; and reported that the total detection rates of parasites in environmental samples in spring, summer, fall and winter were 25.0% (18/72), 22.2% (24/108), 16.7% (18/108), 29.6% (32/108), and 29.6% (32/108), respectively. Coccidia were detected in all four seasons, with the lowest detection rate of 5.6% (6/108) in the fall and the highest detection rate of 20.8% in the spring. An investigation into the epidemiology of coccidia in environmental samples from large-scale sheep farms revealed a total detection rate of 16.7% (85/712) (Zhao 2023). The detection rate of environmental and stool samples from large-scale sheep farms in Henan Province was significantly lower than that in Ningxia Province (14.9%, 29/195 vs 11.1%, 56/504). Environmental pollution may be a significant factor in the development of coccidiosis in sheep raised in large-scale housing. Therefore, it is recommended that clinical practice focus on improving the cleaning, sanitation, drying, and ventilation of sheep houses and their environment to prevent and control coccidiosis infection effectively.

In fecal samples from free-range grazing sheep, coccidia infection rates were high (88.0%, 88/100); however, coccidia were not detected in environmental samples (Zhao 2023). This is because the sandy and dry climate of Ningxia is not conducive to the development of coccidia oocysts to the infection stage. It is suggested that areas with a large range of activities for free-range sheep, low stocking density, and a dry climate, such as Ningxia, should strengthen the planned prevention and control of coccidia in sheep. To improve environmental and sheep parasite detection and monitoring, targeted prevention and control measures that consider climate and geographical conditions are recommended. Large-scale sheep farms should strengthen parasite detection and monitoring efforts and implement planned and targeted deworming measures. It is important to maintain clean, hygienic, and dry sheep sheds and their surroundings. Additionally, manure must be treated in a harmless manner and utilized comprehensively to prevent environmental parasites, contamination, and the spread of pathogens.

Sheep and goat coccidiosis are widespread across the country. Adult sheep have some immunity to coccidiosis and therefore shed only a small number of oocysts when reinfected. However, lambs have low immunity, and the number of oocysts per gram (OPG) of feces excreted by infected sheep for the first time can reach 1 million (Bangoura and Daugschies 2007). Therefore, ewes housed together can easily transmit coccidia to lambs, resulting in widespread infection (Carrau et al. 2018). Oocysts can remain active and infective for up to one year after being shed into the environment, increasing the risk of coccidia transmission. The *Eimeria* oocyst wall is very thick, making it resistant to ordinary chemical and physical methods as well as extreme environmental changes such as cold, pH changes, and low-oxygen environments. Coccidia oocysts thrive in moist and cool environments (Marquardt et al. 1960); therefore, to some extent, controlling the spread of coccidiosis can be achieved by keeping the pens dry and well ventilated.

Control and prevention strategies

Currently, pharmaceutical interventions and effective management strategies are the principal methods for preventing and treating coccidiosis in sheep and goats.

Management practices

Effective husbandry management is essential for controlling and preventing coccidia infection. Maintaining a sanitary environment in a barn is crucial, and the routine removal of feces and disinfection of the barn can substantially diminish the risk of coccidia transmission (Keeton and Navarre 2018b). Second, a rotational grazing system is extensively implemented to minimize sheep and goats' exposure to contaminated pastures by frequently altering the grazing locations, hence decreasing the prevalence of coccidia infection. The supply of clean drinking water and balanced feed enhances the flock's general immunity and mitigates the severity of coccidia infection (Adali 2014). Moreover, judicious management of flock density can significantly mitigate cross-infection among sheep (Adali 2014). While management methods are crucial in mitigating coccidiosis, they must be integrated with additional preventive strategies to achieve the best outcomes.

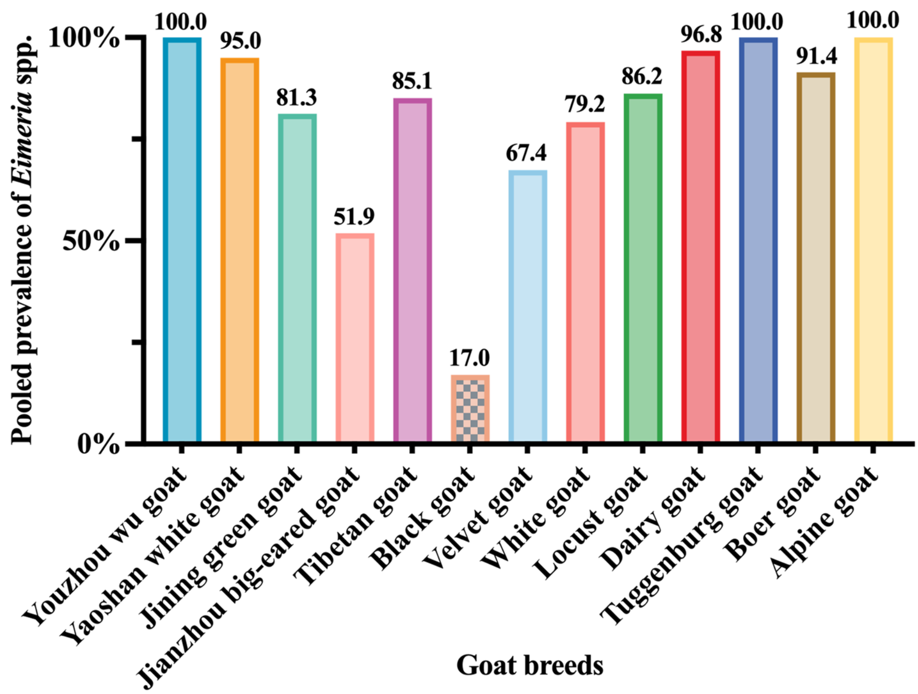

Fig. 8 Pooled prevalence of *Eimeria* spp. in different goat breeds in China

Chemical drugs

Chemicals are currently among the most commonly used techniques for reducing coccidiosis in sheep and goats. Frequently utilized compounds include sulfonamides, diclazuril, clopidol and amprolium. Sulfonamides, including sulfamethoxazole and sulfadimethoxine, effectively suppress the proliferation of coccidia and demonstrate considerable therapeutic efficacy, particularly during the initial phases of coccidia infection (Zhang 2013; Zhang and Wang PY. 2014). Diclazuril is a powerful anticoccidial agent that inhibits the growth of coccidian sporozoites and is extensively utilized in the prevention of coccidiosis in ovine and caprine species (Zhang and Wang PY. 2014). Clothianidin and ampicillin are frequently employed to prevent coccidia infections by obstructing particular stages in the coccidia life cycle, hence diminishing their transmission (Zhang and Wang PY. 2014; Zong, et al. 2014). Prolonged use of chemical medications often results in drug resistance, significantly diminishing their efficacy, making the investigation of novel pharmaceuticals or coadministration procedures a priority for future studies.

Although chemical drugs and management strategies are effective in preventing and controlling coccidiosis, issues such as resistance, drug residues, and environmental pollution resulting from prolonged use of anticoccidial agents have necessitated the ongoing pursuit of safer and more sustainable alternatives (Zi et al. 2019). In this context, natural compounds such as herbs and probiotics have garnered increased interest as novel anticoccidial agents. Recent research has indicated that herbs can directly decrease coccidia reproduction through various active components and mitigate coccidia infections by bolstering the host's immune function (Lei and Jiang 2023). Moreover, the use of probiotics, a crucial method for managing the equilibrium of intestinal bacteria, has demonstrated potential utility in the prevention and management of coccidia infections. Probiotics are anticipated to serve as effective adjuncts against coccidia because of their inherent antibacterial and immunomodulatory properties (Awais et al. 2019).

Chinese herbal medicines

Chinese herbal medicines can not only produce strong inhibitory effects to prevent and treat coccidiosis but also have the advantages of few side effects, low cost, and ease of use. Importantly, Chinese herbal medicines can enhance the physical fitness and health of sheep and immunity, promoting the healthy growth of sheep (Park et al. 2012). Currently, Chinese herbal medicines are commonly used to prevent and treat coccidiosis in chickens and rabbits. Augustine reported that the invasion of *E. tenella* and *E. acervulina* sporozoites was significantly reduced in chicks fed diets containing betaine or salinomycin (Augustine et al. 1997). Daneshmand investigated the effects of a processed sugarcane extract on the viability of avian *Eimeria* sporozoites (Daneshmand et al. 2021). Polygain™ decreased the counts of *E. maxima*, *E. acervulina*, *E. bruneti*, and *E. mitis* sporozoites to a level similar to that of salinomycin ($P > 0.05$). Yan reported that treatment with Eupatorium adenophorum extract reduced the sporulation rate of Coccidia oocysts and weakened their activity (Yan et al. 2019). Huang reported the effects of Phytolacca, Pulsatilla, Changshan, Agrimony, and Honeysuckle on the immune organs and growth performance of coccidia-infected chickens (Huang et al. 2010). This study demonstrated that the Chinese herbal preparation improved the performance of coccidia-infected chicks, as well as their growth and development of immune organs. Wang also reported that *Houttuynia cordata*, garlic and *Portulaca oleracea* can significantly reduce the relative reduction rate of oocysts in Hu sheep (Wang 2022).

Probiotics

Probiotics have received increasing attention in recent years as natural anticoccidial means. Previous studies have demonstrated that probiotics can effectively prevent coccidiosis (Jiao et al. 2021). Cao reported that *Bacillus subtilis*, Lactobacillus and yeast have protective effects on *E. tenella*-infected chickens, which can significantly improve the survival rate of infected chickens (Cao 2018), improve intestinal mucosal immune function, and play a role in anticoccidiosis. The results of the probiotic anti-coccidia infection test revealed that the composite probiotics consisting of *Lactobacillus johnosonii*, *Bacillus subtilis* and *Diutina rugosa* can significantly enhance the anti-coccidia infection effect on chickens, and the anti-coccidia infection effect was greater when the ratio of probiotics was 1:1:1 (Du 2020). A new compound cream probiotic was designed, screened and prepared by selecting *Bacillus subtilis*, *Enterococcus faecalis*, *Saccharomyces cerevisiae* and *Clostridium butyricum*. This study indicates that probiotics can increase the number of beneficial bacteria and control the disorder of the microbiome caused by naturally coccidia infection, thus reducing diarrhea symptoms, but the effect of artificial coccidia infection is not obvious, indicating that probiotic preparations have difficulty resisting the one-off infection of larger doses of coccidia (Lu 2023). The precise anticoccidial mechanisms of probiotics remain poorly defined, necessitating additional investigation into their modes of action in the prevention and management of coccidiosis, particularly regarding their possible role in host immunomodulation.

Presently, the prevalent strategies for managing coccidiosis in sheep and goats primarily depend on chemical drugs and effective management techniques. Despite the efficacy of these treatments, future research should prioritize natural alternatives, such as probiotics, prebiotics, and botanicals, in light of concerns over medication resistance and environmental pollution. The fermentation of herbs combined with probiotics has significant potential and is anticipated to become the next generation of coccidiosis management.

Conclusion remarks

Sheep coccidiosis is a prevalent parasitic affliction induced by protozoa of the genus *Eimeria*, impacting sheep and goats of all breeds and ages, particularly lambs aged 1–3 months. Owing to the underdeveloped immune system of lambs, pathogens can proliferate swiftly postinfection, resulting in severe health complications and considerable economic damage. The mortality rate in lambs infected with coccidia might reach 60.0% (Gong 2022). The disease is prominent in spring, summer, and autumn, but low winter temperatures impede oocyst growth and decrease its occurrence. An extensive examination of the epidemiological characteristics, regional and temporal distributions of coccidiosis, and influencing factors is essential for formulating effective preventative and control strategies.

The transmission mechanism of coccidiosis is intricate, with both direct contact between infected and healthy sheep and environmental oocyst contamination serving as significant transmission pathways (Chang 2021). Consequently, prevention is paramount in managing coccidiosis. Optimizing feeding management, enhancing nutritional supplies, maintaining cleanliness in sheep housing, judiciously regulating grazing density, and reinforcing quarantine measures are all useful preventive tactics. The efficacy of prevention and control can be augmented by including preventative anti-coccidia medications and implementing temporal and geographical monitoring and early warning systems.

Nevertheless, the extensive application of anticoccidial agents has exacerbated issues of drug resistance and residue, limiting the sustained efficacy of these conventional approaches. The development of safe, efficient, and low-toxicity alternative anti-coccidia pharmaceuticals has emerged as a significant focus of contemporary studies.

Chinese herbs, particularly those that share origins with food and medicine, present significant potential for use because of their natural, nonpolluting, and side effect-free properties. These herbs not only suppress pathogenic germs but also exhibit several actions, including immunomodulation and antibacterial growth stimulation, thereby enhancing animal health. Thorough investigations of the active constituents of herbs and their mechanisms of action present significant potential for future applications in the prevention and management of coccidiosis.

Probiotics exhibit potential utility in combating coccidiosis by modulating the gut microbiota, bolstering immunity, and facilitating growth. Research indicates that probiotics can impede coccidia infections by strengthening intestinal barrier integrity, reducing intestinal inflammation, and competing for ecological niches. Nevertheless, the majority of existing research has been on poultry, particularly chickens, with comparatively limited investigations undertaken on ruminants such as sheep and goats. Consequently, subsequent investigations will concentrate on the utilization of probiotics for the prevention and management of coccidiosis in sheep. While the utilization of probiotics in animal feed has potential, further research on the ideal dosage and time is necessary to enhance their effectiveness in practical production, given the great diversity of species and application methods.

This review highlights the advancements in epidemiological research on coccidiosis caused by the genus *Eimeria* in sheep and goats in China. Despite achievements in understanding the mode of transmission and impact of these parasites, more in-depth studies are needed in the future to develop more effective prevention and control strategies to mitigate the economic and health impacts of coccidiosis on China's livestock industry.

Abbreviations

PCR	Polymerase chain reaction
RT–PCR	Real-time fluorescence quantitative PCR
HRM	High-resolution melting analysis
LAMP	Loop-mediated isothermal amplification
nano-PCR	Nanoparticle-assisted PCR
RFLP-PCR	Restriction fragment length polymorphism polymerase chain reaction
18S rRNA	18S ribosomal ribonucleic acid
COI	Cytochrome C oxidase subunit I
ITS	Internal transcribed spacer
DNA	Deoxyribonucleic acid

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s44149-024-00151-w.

Additional file 1: Table S1. Morphological characteristics of coccidia infecting sheep and goats in our laboratory.

Additional file 2: Table S2. Prevalence of sheep *Eimeria* spp. in different regions of China.Table S3.Prevalence of goats *Eimeria* spp. in different regions of China.

Additional file 3: Table S4. Total infection rate of *Eimeria* spp. in sheep and goats under different breeding modes.Table S5.Pooled prevalence of *Eimeria* spp. in different goat and sheep breeds.

Authors' contributions

Fuchun Jian conceived and designed the review. Manyu Liu analyzed the data and wrote the original draft of the manuscript. Senyang Li, Shucheng Huang, Longxian Zhang, Fuchun Jian and Manyu Liu revised the final manuscript. All the authors read and approved the final manuscript.

Funding

This study was supported, in part, by Key Research and Development Projects of Henan, China (231111111600), the National Key R&D Program (2023YFD1801200), and the China Agriculture (sheep and goats) Research System (CARS-38).

Data availability

All of the data generated or analyzed during this study are included in this manuscript.

Declarations

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no conflicts of interest associated with this study.

Received: 5 September 2024 Accepted: 15 November 2024
Published online: 23 December 2024

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