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REVIEW ARTICLE

BIBLIOMETRIC ANALYSIS OF RESEARCH TRENDS AND HOTSPOTS IN THE FIELD OF FOREST MUSK DEER (*Moschus berezovskii*)

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ABSTRACT

The forest musk deer (FMD) (*Moschus berezovskii*) represents an endemic and endangered species in East Asia, valued for biodiversity conservation and musk economy. In recent decades, various research has investigated the ecology and biology of FMD. However, a bibliometric analysis is currently missing. This work, for the first time, elucidates the current research trends and hotspots of FMD by analyzing annual publication volume, citations, samples, and keywords from FMD-related publications in two prominent databases: the Web of Science (WoS), and the Chinese National Knowledge Infrastructure (CNKI). The results reveal that (1) both WoS and CNKI publications exhibit fluctuating growth patterns, with CNKI initiating earlier (in 1958) than WoS (1990), however, WoS publications have recently surpassed CNKI. (2) Highly cited WoS articles primarily concentrate on the micro-ecology of captive FMD, whereas highly cited CNKI literature highlights the macro-ecology of wild FMD. (3) CNKI research encompasses a broader array of samples compared to WoS studies. (4) The Citespace keyword timeline maps indicated that WoS research centered on subjects such as "microsatellite loci" and "gut microbiota," while CNKI studies prioritized themes like "camera trap" and "musk," alongside a global emphasis on the "musk gland." Research on FMD reveals significant developmental potential, yet numerous areas remain underexplored. The current FMD study mostly focuses on disease mechanisms and musk secretion in captive populations. However, research on ecology and the conservation of wild populations is seriously lacking. Future studies should focus on key research areas such as FMD rewilding and reintroduction programs, non-invasive sampling techniques, synthetic musk, and gut probiotics. Pertinent research will inform conservation and sustainable utilization practices for FMD.

Keywords: Forest musk deer; *Moschus berezovskii*; Web of Science; Chinese National Knowledge Infrastructure; Citespace.

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INTRODUCTION

The forest musk deer (FMD) (*Moschus berezovskii*), a small hornless hoofed animal (Artiodactyla; Moschidae), mainly distributed in China and northern Vietnam (Zhou *et al*., 2004). The musk produced by male FMD is a precious material for conventional medication and fragrance (Sheng, 1996). In the early 1900s, wild FMD was widespread in Southeast Asia (Feng *et al*., 2023). From the 1960s to the 1990s, due to the impact of road construction and farmland expansion, FMD habitat became fragmented, with the distribution range shrinking drastically. Subsequently, extensive hunting and poaching occurred owing to the elevated cost of musk (Wang *et al*., 2010), with grazing, mining, and other activities further compressing the wild FMD habitat, leading to its endangered status and local extinction in some regions (Wu and Wang, 2006). This situation began to improve in 1979 when *Moschus* spp. was included in CITES, drawing international attention to conservation efforts. In 2003, China, a key country in the distribution of FMD, designated FMD as a protected animal (Gao *et al*., 2005) and implemented the Wild Animals Protection Law to strengthen FMD protection (Wu and Wang, 2006). *Moschus berezovskii* includes four recognized subspecies: *M. b. berezovskii*, *M. b. bjiangensis*, *M. b. yunguiensis,* and *M. b. caobangis* (Grubb, 2005). *M. b. anhuiensis* was once included but is now considered an independent species closely related to *M. b.* (Yang *et al*., 2019).

The captive breeding of FMD is essential to restoring wild populations and encouraging the persistent use of musk supplies (Chang *et al*., 2018). Male FMD have a musk-producing organ located in the abdomen. Following sexual maturity, musk is secreted annually in small quantities to attract females and mark territories

(Sheng, 1996). Musk exhibits pharmacological properties, such as mediating the central nervous system and treating cardiovascular diseases (Yang *et al*., 2024), and thus serves as a critical component in renowned traditional medicines (Feng *et al*., 2023). The captive FMD population has significantly increased over the past few decades, with China's musk production leading globally (Sheng, 1996). Nevertheless, a considerable supply-demand gap persists, and the price of musk skyrocketed from 60 RMB per gram in 2005 to 800 RMB per gram in 2018 (Chang *et al*., 2018), earning it the metaphor "soft gold." Despite this, the high physiological stress caused by the relatively short domestication history; inbreeding depression triggered by the lack of germplasm resources; and high morbidity and mortality rates remain urgent challenges within the domestication industry (Pei and Wu, 2007; Wang *et al*., 2010).

With continuous technological advances, researchers have expanded their knowledge of the conservation and breeding of the FMD, including geographical distribution (Xiao *et al*., 2008; Cha *et al*., 2019), feeding habits (Su *et al*., 2023; Jiang *et al*., 2023), infant rearing (Du and Sheng. 1997, 1998), the secretion of musk and its chemical composition (Li *et al*., 2016; Jie *et al*., 2019), genetic diversity (Zhao *et al*., 2011), diseases (Deng *et al*., 2022; Ding *et al*., 2022), stress and personality (He *et al*., 2014; Ding *et al*., 2022; Li *et al*., 2022), gut microbiota (Hu *et al*., 2017; Yang *et al*., 2021), etc. Although multiple studies on FMD covering various aspects have been published, there is an absence of bibliometric articles to identify current research hotspots and emergings. The present study is the first bibliometric study on the FMD. Here, a total of 467 selected English and Chinese articles were collected from two databases: Web of Science (WoS); and Chinese National Knowledge Infrastructure (CNKI), and the yearly publication volumes, citations, sample categories, and research hotspots of the literature were analyzed. Our findings could elucidate the principal features and evolving patterns of FMD research, uncover neglected areas, and offer recommendations for prospective research directions.

MATERIALS AND METHODS

Literature search scheme: The English literature was derived from the Web of Science Core Collection™ (https://www.webofscience.com, retrieved on June 4, 2024) (WoS). WoS is an internationally recognized scholarly resource database covering papers across a wide range of various fields, such as natural sciences, engineering, medicine, and social sciences. The WoS Core Collection is a curated subset of WoS and includes articles of high academic value and impact in the WoS database; hence, the WoS Core Collection was utilized to search for FMD papers written in the English language (This restriction applies only to literature published after 2004, as the concept of WoS Core Collection was introduced that year). The Chinese literature was gathered from the CNKI and is accessible at https://www.cnki.net (retrieved on June 4, 2024). CNKI represents the largest academic database in China, encompassing more than 90% of the nation's scientific literature resources, which include journal articles, academic dissertations, etc. The search formula in WoS was input as "TS = (*Moschus berezovskii* OR forest musk deer NOT *Moschus chrysogaster* NOT *Moschus moschiferus*)", while the formula of CNKI was set as "{Theme = ("Forest Musk Deer")}". The publication year was limited to 2023 and earlier. Articles published in 2024 were excluded since the year was not yet complete at the time of literature collection. The original records were then manually filtered by carefully reading the title and abstract to exclude non-ecological, non-biological, duplicate, non-experimental, review, and conference papers. Notably, a significant portion of the literature focused on the therapeutic effects of medicinal musk, so these papers were removed. After document cleansing, a total of 131 WoS and 336 CNKI valid documents were generated, which were directly related to FMD in the title, keywords, and paper's main body.

Literature analysis strategy: The information from filtered WoS and CNKI literature, including publication year, citation count (as of the retrieval date), and sample type, were input into Microsoft Excel 2019 for pivot table analysis, and then line and pie charts were created. CiteSpace (Version 6.3.1) was used to draw a keywords timeline map. Citespace is a JAVA-based software (Chen, 2004), which visualizes features of extensive documentation and has, therefore, been frequently utilized in prior bibliometric studies (Guo *et al*., 2022). Citespace uses "centrality," i.e., the frequency of a node acting as the shortest bridge among other nodes, to calculate the weight of the node. Nodes of high centrality are considered hot academic topics during that period. The formula for centrality is as follows:

$$\text{Centrality（Node}_i\text{）} = \sum_{i\neq j\neq k} \frac{P_{jk}（i）}{P_{jk}}$$

Note: P_{jk} denotes the count of minimum distance routes connecting nodes j, and k, whereas $P_{jk}（i）$ quantifies the count of routes that traverse node$_i$.

In terms of keyword clustering, Log-Likelihood Ratio (LLR) computation strategy of CiteSpace was chosen to cluster topic words in WOS and CNKI documents, and the LLR computational formula is as follows:

$$\text{LLR} = \log\frac{p（C_j|V_{ij}）}{p（\overline{C_j}|V_{ij}）}$$

Note: LLR represents the log-likelihood of the topic word V_i for class C_j. The terms $p（C_j \mid V_{ij}）$ and $p（\overline{C_j} \mid V_{ij}）$ denote the probability density functions in class C_j

and $\overline{C_J}$, respectively.

The arguments for CiteSpace are detailed as follows: The time splitting was established at one year, while the refined g-index was configured to k = 25, selecting the top 25 keywords from each time slice. The network cropping algorithm utilized was "pathfinder". Other parameters were set to their default values. In CiteSpace mapping, the quality of clustering was evaluated through the modularity value (Q) and the silhouette value (S). A Q value > 0.3 indicates a remarkable clustering composition. A S value > 0.5 demonstrates the clustering class is appropriate; A S value > 0.7 demonstrates the clustering class is convincing (Guo *et al*., 2022).

RESULTS

Annual academic publication: The number of FMD publications displayed an overall increasing trend during the past several decades (Figure 1). The two earliest FMD studies of WoS literature were initiated in 1990 and 1999, respectively. Fontana and Rubini analyzed karyological data on the FMD and concluded that it should be placed in a separate family, Moschinae (Fontana and Rubini, 1990); Su *et al*. analyzed all Moschus species' mitochondrial cytochrome b genes and found that FMD lineage split from musk deer's common ancestor 370,000 years ago (Su *et al*., 1999). From 1990 to 2017, the annual WoS publication output remained low (average < 10). However, between 2018 and 2023, a significant acceleration was observed, with a surge to an average of 14.83, peaking at 19 articles in 2021.

For CNKI literature, the two earliest traceable articles were published in 1958, predating the WoS literature. One article provided a preliminary description of FMD's life history (Bai, 1958), while another report explored the FMD domestication techniques, including an overview of FMD's preferred green forage during different seasons (Liu, 1958). The annual publication volume in CNKI shows a fluctuating upward trend with two notable peaks. The first growth period spans from 1958 to 1992: between 1958 and 1981, the annual publication volume grew slowly, averaging 2.50 articles per year; from 1982 to 1988, this number rose to an average of 6.86 articles per year. The first peak occurred in 1989 and 1990, with 21 articles published annually, followed by a decline to 7 articles in 1991. The second growth period extends from 1992 to 2023: from 1992 to 2006, the annual publication volume remained low, with fewer than five articles per year. From 2007 to 2017, the publication volume increased, averaging 8.73 articles per year. A significant rise occurred between 2018 and 2023, with an annual average of 15.33 articles, peaking in 2019 and 2021 at 18 articles per year.

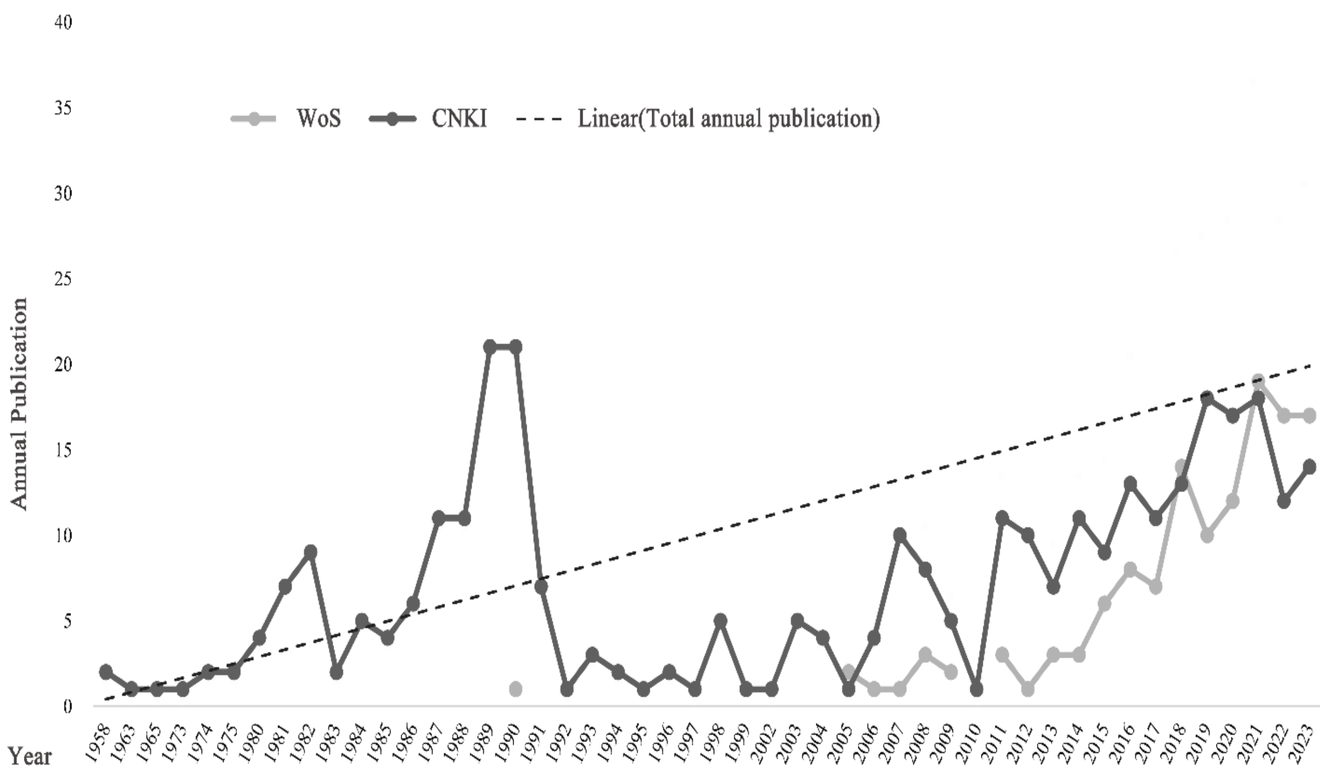


Figure 1: Global annual publications on forest musk deer research (1958−2023)

Citation: Examining the citation indexes of a paper can reflect its recognition by the academic community after publication. For WoS literature, papers related to FMD have been cited 1396 times (average: 10.82 citations), while CNKI literature focusing on FMD has been cited 2611 times (average: 11.92 citations), which is higher than WoS. The percentage of WoS studies cited more than five times was 58.91%, whereas for CNKI literature, this figure was 60.27%.

Table 1 presents the top 5 most cited articles on FMD from two literature databases. Highly cited WoS articles primarily focused on FMD's gut microbiota (Li *et al*., 2018), chromosomal data (Fontana and Rubini, 1990; Su *et al*., 1999), musk chemistry (Li *et al*., 2016), and pathogens isolation (Zhao *et al*., 2011). In contrast, CNKI's most cited literature showed a higher interest in habitat prediction (Luo *et al*., 2011), behavioral rhythms (Gao, 1963; Du and Sheng, 1998; Jia *et al*., 2014), taxonomy (Gao, 1963), and time allocation (Du and Sheng, 1998).

Table 1. The top 5 most cited studies on forest musk deer in WoS and CNKI literature.

Rank	Publish year	Title	Impact factor (5 years)	Citations
1	2018	Comparison between the fecal bacterial microbiota of healthy and diarrheic captive forest musk deer	5.1	95
2	1990	Chromosomal evolution in Cervidae	1.8	87
3	1999	Phylogenetic study of complete cytochrome b genes in musk deer (genus *Moschus*) using museum samples	3.8	77
4	2016	The musk chemical composition and microbiota of Chinese forest musk deer males	4.3	50
5	2011	Detection and characterization of antibiotic resistance genes in *Arcanobacterium pyogenes* strains from abscesses of forest musk deer	2.5	50
1	2011	Habitat prediction for forest musk deer (*Moschus berezovskii*) in Qinling mountain range based on niche model	4.4	139
2	2014	Seasonal activity patterns of ungulates in Qinling Mountains based on camera-trap data	2.6	138
3	1963	Taxonomy of Chinese musk deer	0.3	65
4	1988	Population density, conservation, and utilization of forest musk deer (*Moschus berezovskii*) on the northwestern edge of the Sichuan basin	1.5	62
5	1998	Time budget and behavior of forest musk deer during lactation	1.5	61

Samples: The samples employed in CNKI literature (Figure 2b) were more diverse compared to those in WoS (Figure 2a). The dominant research samples in WoS literature, ranked in descending order of usage, were feces (23.5%), blood (10.5%), and lungs (6.8%). In contrast, in CNKI literature, behavioral data (15.43%), feces (11.02%), and lungs (7.1%) were the most utilized specimens. Conversely, some samples received constrained attention, such as drinking water (WoS: 0.6%) and mineral lick (WoS: 0.6%).

Keywords timeline map for WoS literature: Literature keywords can function as a "window" into the frontiers and evolving trends within a large body of literature. The keyword timeline maps were generated using the LLR algorithm in CiteSpace. The quality control indicators for WoS clustering were Q = 0.7654 (>0.3) and S = 0.9323 (>0.7) (Figure 3a); for CNKI clustering, Q = 0.7041 (>0.3) and S = 0.9755 (>0.7) (Figure 3b). Therefore, the clustering structures are significant and fulfill the research objectives of this study.

In the keyword timeline characteristics of WoS literature (Figure 3a), "#0 complete cytochrome b gene" (centrality: 0.65) and "#1 chromosomal evolution" (centrality: 0.96) reflect an emphasis on the genetic diversity and evolutionary research of FMD. The entire mitochondrial genome of FMD was delineated by Peng *et al*. in 2009, demonstrating that Moschidae is a sister group to Cervidae/Bovidae (Peng *et al*., 2009). Yang *et al*. performed additional research and determined that Moschidae is most closely associated with Bovidae (Yang *et al*., 2018). Fan *et al*. produced the whole genome draft and gene annotation for FMD (Fan *et al*., 2018). These findings enabled an understanding of the genetic basis for FMD biological traits. With the advancement of technology, the application of diverse molecular techniques has been continuously increasing in FMD research. Qiao *et al*. identified the encoding genes of zinc-finger protein located on the X and Y chromosomes (ZFX/ZFY) as genetic markers for the swift determination of FMD sex (Qiao *et al*., 2007); Liu *et al*. characterized the FMD fecal viral metagenomics, revealing a diverse range of CRESS-DNA viruses (Liu *et al*., 2020); Sun *et al*. conducted blood transcriptomes from purulent and healthy FMD to explore the mechanisms underlying abscess formation (Sun *et al*., 2018).

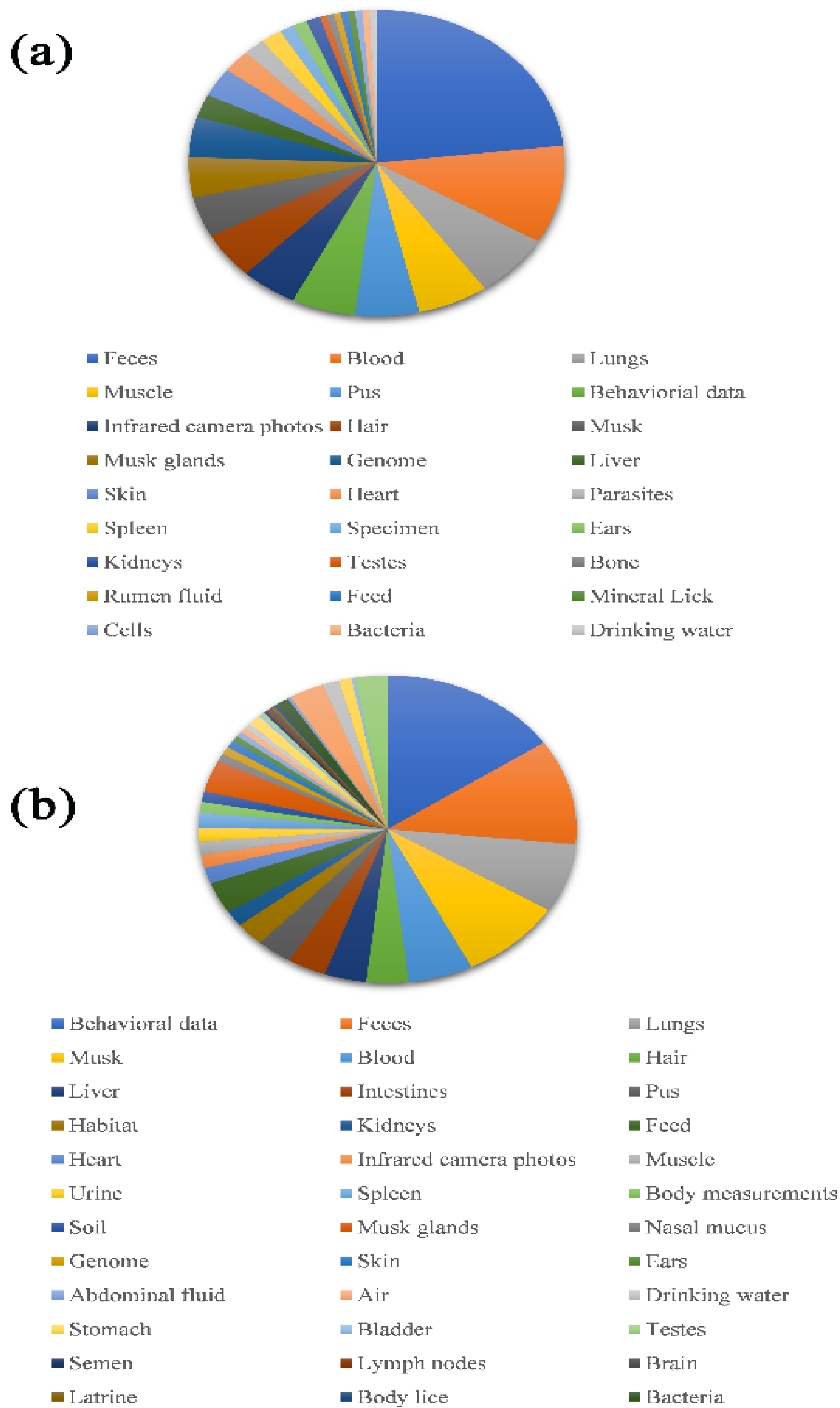


Figure 2: Sample classification in forest musk deer research. (a) Web of Science; (b) CNKI

"#2 microsatellite loci" (centrality: 0.73), also known as simple sequence repeats, has been widely employed as second-generation molecular markers in several scientific domains, including animal genetic diversity and gene mapping (Guan *et al*., 2009). These markers have been demonstrated to be polymorphic in captive FMD populations (Guan *et al*., 2009). Microsatellite loci can help clarify the origins and histories of different FMD populations, including the effects of genetic bottlenecks, hence facilitating the genetic management tools of FMD populations. Comparably, In module "#4 endangered forest musk deer" (centrality: 0.13), the major histocompatibility complex (MHC) is a key topic. Previous studies have shown that the DRB gene of MHC-II in FMD exhibits considerable variability and evolutionary potential through comparisons with other species (Xia *et al*., 2016). This finding is significant, as MHC plays a crucial role in binding extracellular antigens and providing protection against infections.

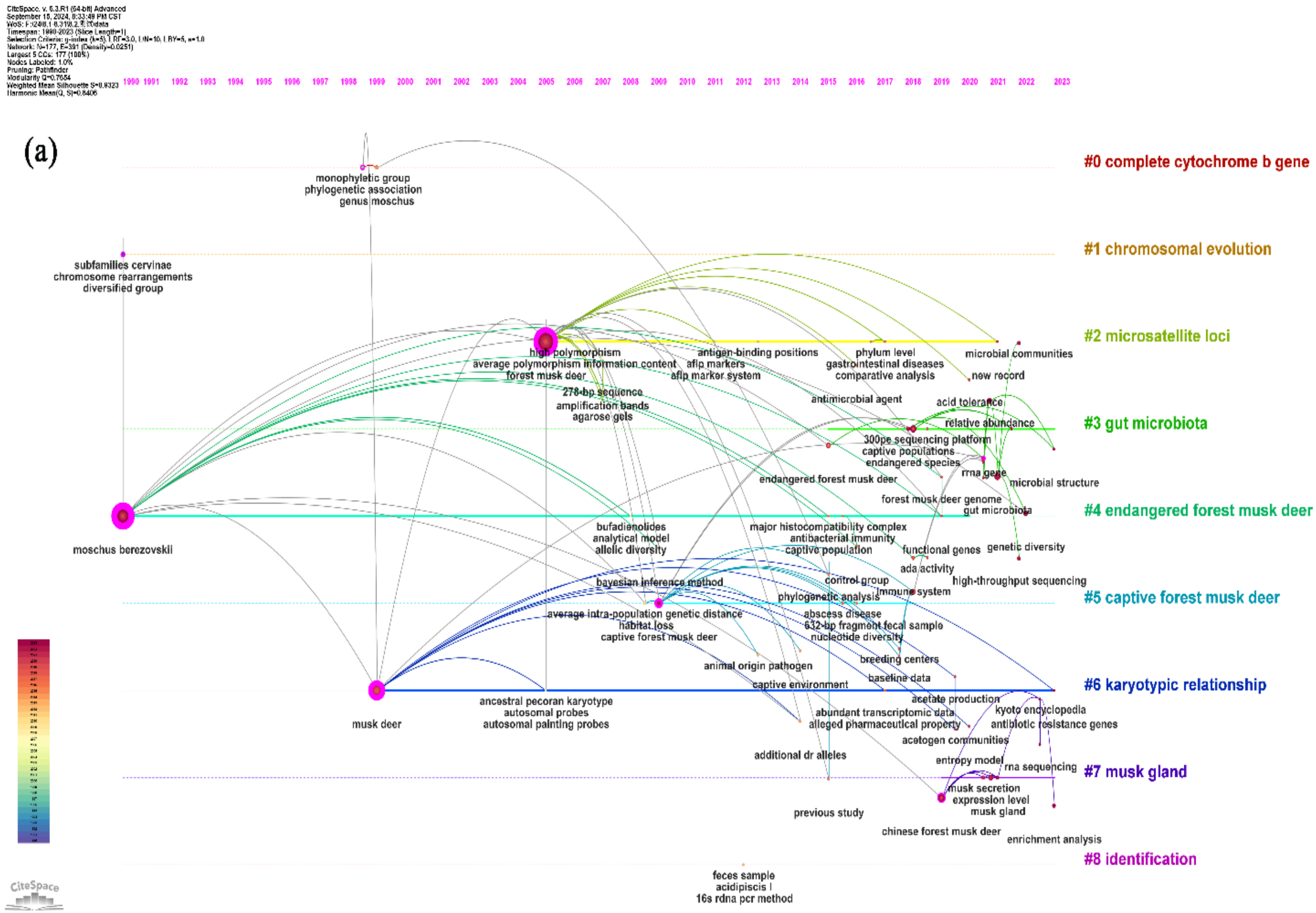
"#3 gut microbiota" (centrality: 0.31) is composed of bacteria, archaea, fungi, viruses, etc., which is essential for mammalian energy metabolism, nutrient absorption, pathogen resistance, and immune function (Li *et al*., 2018). Non-invasive fecal sampling has been utilized to investigate the FMD gut microbiota, encompassing various influencing factors such as host taxonomy (e.g., compare with *Moschus chrysogaster*) (Hu *et al*., 2017), gender, age (Zhao *et al*., 2019), dietary interventions (e.g., probiotics) (Yang *et al*., 2021). These research offer the framework for understanding host-microbe co-evolution, monitoring FMD health through digestive symbionts, and optimizing compound feeds.

"#5 captive forest musk deer" (centrality: 0.06) encompasses studies on FMD abscess disease, which is a major health threat responsible for over 50% of FMD mortality (Liu, 2004). This disease is characterized by disseminated suppurative infections that can spread from external injuries to internal organs (Zhao *et al*., 2011), generally leading to irreversible death (Liu, 2004). Up to 12 bacterial species, including *Trueperella pyogenes*, *Bacillus cereus*, and *Pseudomonas aeruginosa*, etc. have been identified in FMD's suppurative organs, with *Trueperella pyogenes* being the most prevalent (Zhao *et al*., 2011). Studies on causative agents of abscess disease could offer insights into potential therapeutic interventions. Recently, DNA vaccines against *Trueperella pyogenes* were developed using chitosan nanoparticles (Huang *et al*., 2018).

"#7 musk gland" (centrality: 0.11) has emerged as a prominent subject in FMD research, incorporating keywords such as "musk secretion" and "expression levels". Musk components are primarily steroidal, including androstane derivatives, cholesterol, wax, and muscone. Unmated male FMD exhibits increased production of muscone and cholesterol (Li *et al*., 2016). Certain bacterial genera and metabolic pathways involved in musk odor fermentation are overrepresented in musk from unmated FMD (Li *et al*., 2016). Jie *et al*. conducted a transcriptomic analysis of the FMD's musk gland, identifying genes in the pathway for synthesizing thyroid hormones that may be linked to musk secretion (Jie *et al*., 2019). These findings hold considerable economic and social value, as they can improve musk production and increase breeders' income.

Keywords timeline map for CNKI literature: In the keyword timeline map of CNKI literature (Figure 3b), FMD macro-ecological measurements appear more frequently compared to WoS literature. In cluster "#0 forest musk deer" (centrality: 1.42), an early research focus is the "mother-infant relationship". The FMD fawns exhibit a "hider" behavior pattern (Du and Sheng, 1996). Fawns generally hide under shrubs from birth until four weeks old, and the mother contacts the fawn through vocalizations. In this "mother-infant" topic, CNKI studies have reported on the fawn's feeding time budget (Du and Sheng, 1997), female FMD's energy metabolism, time allocation, and behavior during pregnancy and lactation (Lin *et al*., 1995; Du and Sheng, 1998). Likewise, "#4 camera trap" (centrality: 0.07) is a commonly employed method in macro-ecology research on FMD. Using camera traps, studies have investigated the FMD's spatio-temporal distributions (Jia *et al*., 2014), sympatric species diversity (Li *et al*., 2022), and habitat range (Jiang *et al*., 2020). Wild FMD habitats include secondary shrubland, evergreen and deciduous broad-leaved mixed forests, and shrub grasslands at altitudes of 800~3200 meters (Feng *et al*., 2023). Despite the protection provided by conservation areas, wild FMD suffer from human disturbance, habitat fragmentation, and low population density (Yao *et al*., 2015). Moreover, global climate change is driving the redistribution of wild FMD to higher altitudes (Jiang *et al*., 2020).

"#1 musk" (centrality: 0.19) focuses on musk secretion, musk glandular cell functions, and its modulation by androgens. Research revealed significant changes in the musk gland's ultrastructure during musk-secretion phases, with glandular cells highly active in synthesizing and secreting proteins during the peak secretion phase (Bi *et al*., 1985). Testosterone levels in FMD blood display a biannual peak pattern, with an initial peak occurring during the musk secretion period, reaching a maximum, and subsequently declining after the secretion period. A secondary peak is observed during the breeding season, followed by a post-mating declination (Yin and Dai, 1990). Exogenous hormones such as luteinizing hormone (LH) have been demonstrated to increase musk production by over 70% (Wang *et al*., 1982). Recent transcriptome sequencing has yielded mRNA and miRNA sequences from the musk gland and musk of FMD, providing important details on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#0 complete cytochrome b gene
#1 chromosomal evolution
#2 microsatellite loci
#3 gut microbiota
#4 endangered forest musk deer
#5 captive forest musk deer
#6 karyotypic relationship
#7 musk gland
#8 identification
monophyletic group
phylogenetic association
genus moschus
subfamilies cervinae
chromosome rearrangements
diversified group
high polymorphism
average polymorphism information content
forest musk deer
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antigen-binding positions
aflp markers
aflp marker system
phylum level
gastrointestinal diseases
comparative analysis
microbial communities
new record
antimicrobial agent
acid tolerance
relative abundance
300pe sequencing platform
captive populations
endangered species
endangered forest musk deer
rrna gene
microbial structure
forest musk deer genome
gut microbiota
moschus berezovskii
bufadienolides
analytical model
allelic diversity
major histocompatibility complex
antibacterial immunity
captive population
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bayesian inference method
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phylogenetic analysis
immune system
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632-bp fragment fecal sample
nucleotide diversity
breeding centers
animal origin pathogen
baseline data
captive environment
musk deer
ancestral pecoran karyotype
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abundant transcriptomic data
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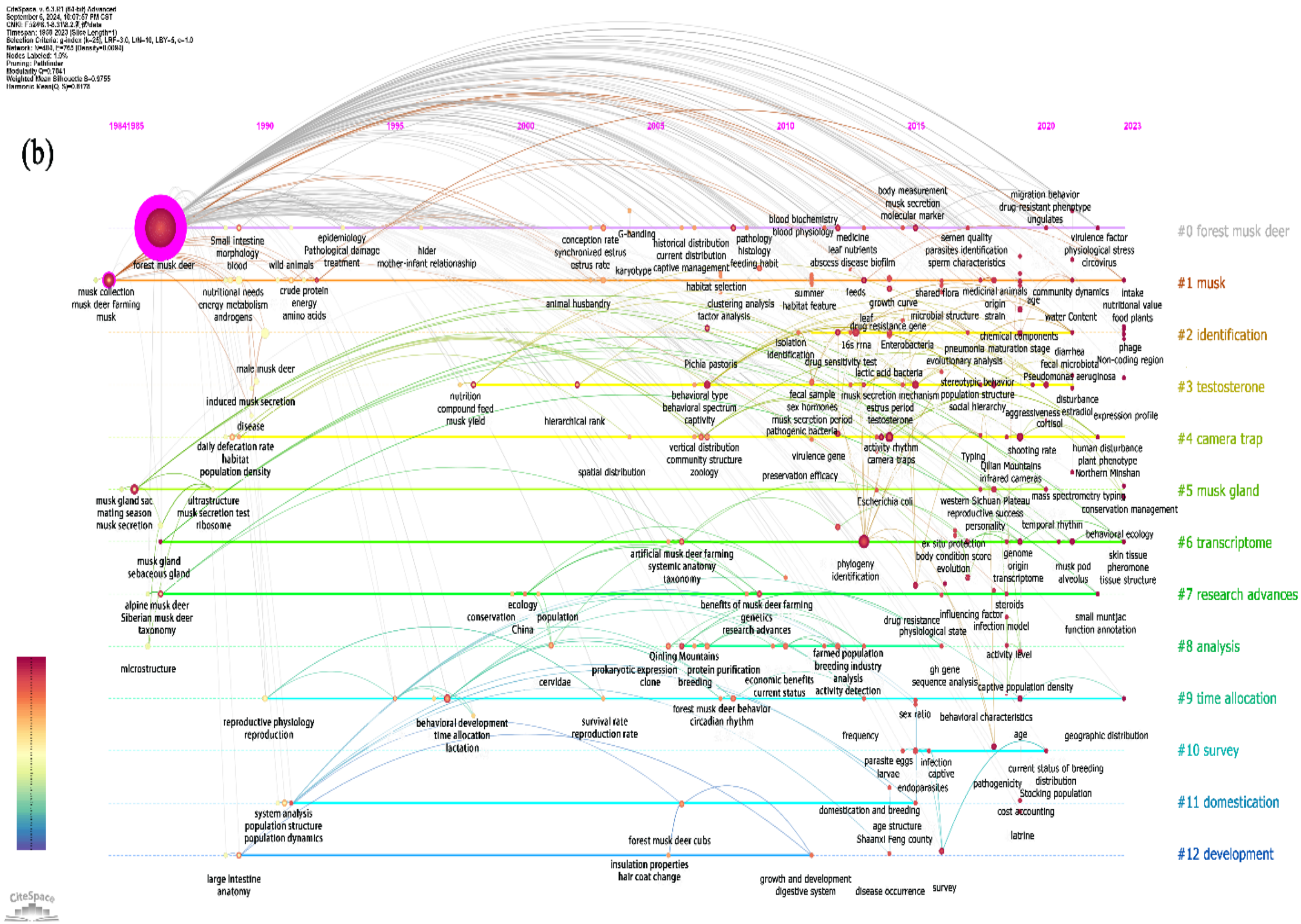

Figure 3: Keyword timeline maps of forest musk deer research. (a) Web of Science; (b) CNKI

the biosynthetic processes of musk (Chen *et al*., 2021).

"#11 domestication" (centrality: 0.01) garnered considerable attention in CNKI literature, with stress identified as a pivotal element in these investigations. Captivity conflicts with FMD's naturally timid and vigilant behavior, introducing various stressors. Chronic stress can reduce immunity and lead to physiological and psychological disorders in FMD (He *et al*., 2014). Prior data showed a significant positive correlation between FMD's stress level and parasite infection intensity (Ding *et al*., 2022). Recently, a remarkable correlation was found between FMD hair cortisol concentration and stocking density (Li *et al*., 2022). Additionally, female FMDs in less crowded conditions showed significantly higher fecal cortisol levels compared to those in more crowded conditions (He *et al*., 2014).

The modules of "#2 identification" (centrality: 0.1), "#7 research advances" (centrality: 0.03), and "#8 analysis" (centrality: 0.02) involved terms such as "isolation," "infection model," "drug resistance," and "prokaryotic expression" etc. Prior research has established acute and chronic pulmonary infection models in mice utilizing *Pseudomonas aeruginosa* derived from infected FMD lungs, subsequently examining medication resistance and efficient treatment strategies for diverse pathogenic strains (Deng *et al*., 2022). The procedure of "prokaryotic expression" entails the amplification of genes encoding immune components, such as IFN-γ from FMD lymphocytes, followed by their cloning. Upon verifying the complete coding sequence, the gene is included into a prokaryotic expression vector and effectively expressed in *Escherichia coli* (Zou *et al*., 2022), creating an outline for further examination of the biological activity of FMD immunological compounds and their potential clinical uses.

DISCUSSION

The increasing upward trend of FMD publications in both CNKI and WoS databases signifies a substantial expansion in FMD research. Significantly, after 2021, the annual publication output in WoS exceeded that of CNKI, indicating an increasing international interest in FMD research. Possible reasons for such trends include the growing recognition of FMD's ecological significance and the economic value of musk, which has attracted interest from pharmaceutical businesses and local governments. Therefore, FMD research is attracting additional funding, consequently propelling the subject forward.

Secondly, highly cited WoS publications concentrate on FMD genetics, pathogen isolation, and musk chemistry, reflecting significant interest in the biological aspects of FMD. Conversely, CNKI literature highlights macro-ecological investigations of FMD, specifically in habitat prediction and behavioral patterns. These disparities may be shaped by regional requirements, scholarly pursuits, and financial resources. Moreover, the highly cited FMD publications in both databases possess low impact factors, suggesting the influence of FMD research needs enhancement. Future initiatives should encourage the submission of FMD papers to high-impact journals and strengthen collaboration with influential disciplines.

Furthermore, CNKI studies exhibit a greater variety of sample types, probably attributable to its earlier start and more extensive body of research. The sampling of FMD could encounter numerous obstacles. Firstly, FMD is a nationally protected endangered species, and live experimentation is forbidden. Invasive sampling primarily entails specimens from naturally deceased individuals, by which degradation and contamination of genetic material may occur. Secondly, wild FMD typically escapes human interaction and resides in inaccessible forests, complicating the collection of fresh samples from wild populations. Third, elevated stress levels in FMD may induce physiological fluctuations during sampling, resulting in inaccurate results. The limited research on FMD stress physiology and disease incidence may be due to such high stress levels associated with FMD. To mitigate these challenges, forthcoming research should integrate traditional samples with those from underexplored sources (e.g., feed, drinking water) and develop novel, non-invasive sampling protocols.

The Citespace keyword timeline maps offer an evolving research perspective over time. The progression of keywords indicates varying research emphases in both domestic and foreign studies. Research on the "musk gland" highlights global interest in both databases. The maps also indicate research deficiencies, notably the insufficient attention given to wild populations in comparison with captive ones.

This study may face the following limitations. Present study was exclusively performed within Web-based frameworks, potentially omitting FMD's paper publications, particularly incipient Chinese materials, which may result in an underestimation of the overall literature. Moreover, the subsequent analysis mostly emphasized the advantageous proportions, which could overlook some under-focus academic works.

Outlook: Based on the current research hotspots of FMD, the following are some suggestions for future research: (1) Increase focus on wild FMD populations: The research on the behavior and ecology of FMD has primarily concentrated on captive populations, leading to considerable deficiencies in comprehending the natural behavior and ecological requirements of wild populations. Future studies should focus on wild populations to address these deficiencies. Climate change is anticipated to modify favorable habitats for FMD (Jiang *et al.*, 2020); however, existing research on these effects is inadequate. Utilization of advanced technology such as remote sensing, GIS, and GPRS is essential for assessing climatic impacts, predicting habitat alterations, and formulating conservation plans. Innovative methods, like drones (Iglay *et al*. 2024), ought to be employed to examine habitat utilization, yielding insights into FMD-environment interactions while reducing human interference. Ecological theories, such as island biogeography, can facilitate enhancing the connectedness of fragmented habitats.

(2) Genetic diversity and conservation strategies: Genetic research predominantly examines captive populations, with insufficient studies on gene flow from wild individuals, particularly in the context of reintroduction programs. Reintroduction initiatives generally emphasize individuals with superior adaptation and reproductive potential. Augmenting investment in the monitoring of genetic diversity and exchange among restored wild populations is crucial for sustainable conservation (Li *et al.,* 2024). In addition, current studies inadequately examine the loss of advantageous genetic traits in captive FMD resulting from founder effects and inbreeding during domestication. Future research should conduct comparisons between captive and wild FMD genomes to clarify this issue.

(3) Musk production and quality: Previous studies on musk production and quality, mainly conducted in the 1980s, were constrained by technological limitations and provided insufficient descriptions of FMD musk gland tissue. The present comprehension of musk secretion pathways is limited, particularly concerning the analysis of multidimensional factors including FMD nutritional requirements, feed processing, genetic breeding, and reproductive influences on musk secretion, in conjunction with genomic and transcriptomic analyses. Furthermore, extra investigation is required to elucidate the differences in clinical efficacy among synthetic musk, and musk from wild and artificially bred FMDs. The intricate composition of musk necessitates an expanded examination beyond muscone, incorporating the bioactivity of additional components and their synergistic interactions.

(4) Nutrition and health management: Captive diets frequently exhibit reduced diversity compared to natural habitats, resulting in inadequate nutritional fulfillment. Future research should concentrate on identifying the specific nutritional requirements of FMD, developing specialized compound feeds, and enhancing feed quality through the diversification of resources, particularly those sourced from natural origins. The absence of technical exchange among breeding centers, alongside nutritional improvements, has resulted in redundant and fragmented research on disease prevention. Collaboration within the industry can establish a systematic framework for disease prevention, which includes examining pathogen resistance, developing rapid diagnostic methods, and improving vaccine formulations to enhance overall disease management. The elevated vulnerability of FMD to diseases and its correlated high mortality rates are likely attributable to insufficient immunity. Consequently, the enhancement of immunity should be a primary focus for future research endeavors. Optimizing gut microbiota, along with the application of probiotics and prebiotics, is crucial for enhancing digestive health and immunity in FMD.

(5) Stress physiology and welfare: The domestication history of FMD is relatively brief, commencing in 1958 in China, which has led to pronounced wild instincts and robust stress responses in neonates. The stress responses negatively impact the reliability of experimental data, as well as the health of FMD, posing considerable challenges in FMD research. Future research must prioritize attempts regarding domestication to establish a steady foundation for genetic breeding, thereby improving the overall development of the FMD industry. Non-invasive sampling techniques, including the collection of feces, urine, and hair, can reduce stress in FMD. Furthermore, developing near-natural breeding models, and examining the connections between stress, immunity, and disease resistance will yield essential insights to enhance welfare, health, and reproductive outcomes.

(6) Technological innovation and cross-disciplinary collaboration: The low impact factors of highly cited articles suggest a limitation in the research influence of FMD. Enhancing impact necessitates the promotion of cross-disciplinary collaboration, an increase in cross-field citations, and the encouragement of high-quality research. Collaborative initiatives across genetics, ecology, and veterinary science are essential. Additionally, promoting international academic collaborations, exemplified by the partnership between China and Vietnam, is essential for elucidating phylogenetic relationships between Chinese and Vietnamese FMD populations, which will strengthen our comprehension of FMD genomics and evolutionary history.

Conclusion: This study conducted the first bibliometric analysis of FMD-related literature from the CNKI and WoS databases, shedding light on research trends, focal points, and regional disparities within the field. The findings reveal a rapid global expansion of FMD research, and significant differences are observed in the types of samples and research themes between domestic and international literature. Based on these results, we highlight current research gaps and propose areas that require further investigation. Continued research will have a profound impact on the scientific conservation and utilization of this economically significant endangered species.

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