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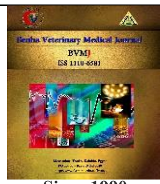

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Review Article

Digitalization of Veterinary Pathology in the Era of Artificial Intelligence: A Comprehensive Review

Ahmed Fotouh

Department of Pathology and Clinical Pathology, Faculty of Veterinary Medicine, New Valley University

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ABSTRACT

The digitalization of veterinary pathology, enhanced by the integration of artificial intelligence (AI), is reshaping the landscape of animal disease diagnosis, education, and research in the era of AI. This transformation involves converting traditional glass slides into high-resolution whole-slide images (WSIs), enabling remote access, long-term storage, and more efficient analysis of tissue specimens. When combined with AI technologies such as machine learning and deep learning, digital pathology offers powerful tools for automated image interpretation, disease classification, and pattern recognition, significantly improving diagnostic speed, accuracy, and consistency. In veterinary medicine, where diversity of species and limited access to specialized pathologists pose particular problems, digital pathology supported by AI provides innovative solutions for both clinical and academic settings. The informatics infrastructure provides storage, recall, and secure dissemination of digital slides and associated metadata among geographically distant institutions, circumventing the past limitations of physical slide transport and specialist availability. Despite hurdles such as high implementation costs, lack of standardized protocols, and the need for large annotated datasets, ongoing advancements and increasing global collaboration are accelerating the adoption of these technologies.

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1. INTRODUCTION

The digitalization of veterinary pathology marks a major shift in how animal diseases are diagnosed, monitored, and managed, aligning veterinary practice with the broader technological advances transforming biomedical sciences. Traditionally, veterinary pathology has depended on well-established methods such as manual light microscopy, hematoxylin and eosin (H&E) staining, and physical handling and storage of slides. Diagnoses have heavily relied on the interpretive skills of individual pathologists examining tissue samples in person, often using analogue tools and limited resources (Ibrahim and Fotouh, 2024). While these methods have served the field for over a hundred years, they face fundamental limitations in accessibility, reproducibility, data handling capacity, and speed issues that are becoming increasingly challenging as the demand for high-volume, standardized, and rapid diagnostic services grows, especially in resource-limited or remote areas (Zuraw and Aeffner, 2022). The development of digital pathology, converting traditional glass slides into high-resolution, navigable whole-slide images (WSIs) with digital slide scanners, provides an effective solution to many of these long-standing problems. These digital images can be stored indefinitely without quality loss, shared across institutions and borders, and accessed remotely using online platforms, removing geographic and logistical barriers to expert diagnosis. AI serves both as a decision-support aid and a way to enhance diagnostic accuracy, helping pathologists by reducing variability and fatigue (Fadhail, 2025). Digital pathology boosts diagnostic accessibility and introduces telepathology, enabling real-time collaboration among pathologists, researchers, and clinicians worldwide. This is especially important during infectious outbreaks, in food animal production, and wildlife health monitoring, where quick diagnoses can reduce economic losses and prevent zoonotic spillovers (Piegari et al., 2018). Additionally, the rise of artificial intelligence (AI), especially machine learning (ML) and deep learning (DL), has further sped up progress in veterinary pathology. Deep learning models like convolutional neural networks (CNNs) can analyze large image datasets to spot intricate histopathological patterns with high accuracy, sometimes matching expert performance. These models can be trained to detect tumors, inflammation, cellular abnormalities, pathogens, or quantify tissue structure features such as mitotic figures, necrosis, and fibrosis with high consistency (Jones-Hall et al., 2022). Integrating AI into digital pathology also creates new opportunities for disease tracking, research, education, and biosecurity. Digitized slides can be stored centrally and systematically annotated, creating large, organized image databases vital for building strong, generalizable AI models and conducting retrospective studies. These databases promote standardization across institutions, support veterinary education through virtual microscopy, and link animal and human disease patterns in One Health initiatives (Turner et al., 2020). The potential of digital and AI-driven veterinary pathology is especially vital amid global challenges like antimicrobial resistance, emerging infectious diseases, climate-induced changes in disease patterns, and food security. In farm animals, early detection of subclinical issues via AI-driven image analysis can lead to prompt action, improving herd health and reducing

* Correspondence to: ahmedfotouh@vet.nvu.edu.eg

losses. In wildlife and exotic animals, where species-specific pathology expertise is scarce, telepathology and AI help democratize access to specialists, supporting conservation and reducing zoonotic risks (Elbarbary et al., 2023; Morsy et al., 2023). However, successfully adopting digital pathology and AI in veterinary medicine must overcome several key technological, regulatory, and infrastructural hurdles. These include the high initial costs for slide scanners and data storage, the need for reliable internet for remote diagnostics, and the lack of standardized imaging and metadata protocols across different species and tissue types. Moreover, AI models trained on limited or biased data sets may perform poorly in real-world situations unless carefully validated across various species, breeds, tissues, and strains (Giacomazzo et al., 2024). Ethical and legal frameworks must also evolve to address issues like data ownership, privacy, and liability in AI-assisted diagnostics. Despite these challenges, the convergence of digital pathology and AI holds great potential to revolutionize veterinary diagnostics. Future workflows will likely become more hybrid, with digital and computational tools complementing rather than replacing human expertise. The role of veterinary pathologists is shifting from sole diagnosticians to multidisciplinary collaborators involved in image analysis, computational modeling, bioinformatics, and global disease monitoring. This review offers a detailed look at the ongoing digital transformation in veterinary pathology, focusing on how integrating AI and whole-slide imaging is shaping the future. It discusses current developments, highlights benefits, examines barriers to widespread use, and suggests future research directions. By doing so, it aims to show how digital and AI-powered pathology are transforming animal healthcare toward a more connected, efficient, and precise future (Ibrahim and Fotouh, 2024).

2. Traditional and digital pathology in veterinary medicine

Veterinary pathology, a key part of animal health care and biomedical research, has mainly depended on traditional diagnostic methods based on manual techniques and analog technologies. Traditional veterinary pathology involves examining stained tissue sections under light microscopes, a critical practice for diagnosing infectious, inflammatory, neoplastic, and degenerative diseases in a wide variety of domestic and wild animals (Ibrahim and Fotouh, 2024). This technique includes various diagnostic methods such as gross pathology, necropsy, histopathology, and cytopathology, all requiring the preparation and analysis of physical glass slides. The process needs skilled staff for slide preparation (fixation, embedding, sectioning, and staining) and experienced pathologists for interpretation. This workflow has provided detailed visual insights into disease processes, which are essential for individual animal health and broader population health management (Piegari et al., 2018).

While traditional methods are reliable and still considered the gold standard in many places, they face logistical and operational challenges. The need for in-person analysis limits access in remote or underserved areas, especially where veterinary pathologists are scarce. Handling slides manually is slow and poorly suited to high-volume workflows. The reliance on physical slides also makes collaboration, second opinions, and integration with electronic health records difficult, hindering multidisciplinary approaches for complex cases. Physical slides are also vulnerable to damage, fading, and loss over time, creating issues for long-term storage and retrospective research (Zuraw and Aeffner, 2022).

In contrast, veterinary digital pathology is a breakthrough that changes how histopathological data are created, analyzed, and shared. It involves scanning entire microscope slides with high-resolution digital scanners to produce whole-slide images (WSIs) that can be viewed, marked up, and studied on digital platforms. These images keep the detailed and diagnostic quality of traditional slides while enabling remote access, long-term storage, and integration with other digital health systems (Piccione et al., 2025). Digital pathology makes telepathology possible, allowing real-time consultations and expert opinions across distances—an especially critical feature in veterinary medicine, where access to specialists (e.g., exotic animal pathology, aquatic species, and zoo medicine) may be limited. A major benefit of digital pathology is its compatibility with artificial intelligence (AI) and machine learning tools, which can analyze WSIs to detect, classify, and measure tissue features automatically. AI can help with routine screening, pattern recognition, and measurement of tissue structures, allowing pathologists to focus on more complex cases while increasing accuracy and efficiency (Pereira et al., 2023). Additionally, digital platforms support image annotation, which helps create labelled datasets needed for training strong AI models and for large-scale research.

Digital pathology also brings major benefits to veterinary education and training. Virtual microscopy lets students explore high-resolution slides online, removing the need for physical slides or lab access. This is especially useful in global education, ongoing professional development, and outreach, where physical samples might not be available. Digital archives also serve as organized collections of rare or classic cases, supporting case-based learning, exam prep, and independent review (Turner et al., 2020). Despite its promise, adopting digital pathology in veterinary practice has hurdles. Buying slide scanners and high-performance computing systems requires significant upfront costs. The large image files need strong storage solutions and cybersecurity measures. There's a steep learning curve for staff unfamiliar with digital processes, and differences in imaging standards, file formats, and platform compatibility can slow data sharing. Regulatory rules for validating and using AI diagnostic tools are still being developed, and standard procedures for creating and testing these systems across different animal types and tissues are limited.

Beyond image analysis, AI is increasingly being utilized for multi-modal data integration, combining clinical records, hematological and biochemical parameters, genomics, microbiome profiles, and even environmental data to support comprehensive, data-driven veterinary care. Machine learning (ML) algorithms such as decision trees, support vector machines (SVMs), and ensemble methods (e.g., random forests, gradient boosting) are used to identify patterns in large, complex datasets that may not be readily apparent through conventional statistical analysis (Bouchemla et al., 2023). In clinical settings, such tools aid veterinarians in differential diagnosis, risk stratification, and personalized treatment planning, thereby facilitating more accurate and timely interventions.

In the context of herd health and production animal medicine, AI systems are proving instrumental in supporting precision livestock farming. Predictive analytics and anomaly detection algorithms are applied to real-time data streams captured from wearable sensors and environmental monitors. These technologies continuously track animal physiology (e.g., heart rate, respiration, rumination), behavior (e.g., movement, feeding, social interactions), and ambient conditions (e.g., temperature, humidity, ammonia levels), enabling early detection of stress, subclinical disease, or environmental hazards (Fadhail, 2025). For example, AI can identify deviations in gait that may suggest lameness or predict mastitis outbreaks by monitoring fluctuations in milk yield and somatic cell counts. These applications contribute to improved welfare, productivity, biosecurity, and resource efficiency, aligning with the principles of sustainable animal agriculture. AI also plays a critical role in veterinary epidemiology and public health surveillance. By aggregating and analyzing data from veterinary clinics, farms, diagnostic labs, and public health agencies, AI models can identify temporal and spatial patterns indicative of emerging disease outbreaks. In doing so, AI enhances early warning systems and supports One Health initiatives aimed at mitigating zoonotic risks. Additionally, AI is being employed in drug discovery and repurposing, where deep learning models are trained to predict molecule–target interactions, screen chemical libraries, and simulate pharmacokinetics/ pharmacodynamics (PK/PD) parameters for veterinary pharmaceuticals.

In veterinary education, AI-driven platforms are revolutionizing traditional learning models. Intelligent tutoring systems, virtual patient simulations, and natural language processing-based virtual assistants provide personalized, interactive educational experiences. These tools allow students to engage in realistic clinical scenarios, receive immediate feedback, and hone their diagnostic reasoning skills in a risk-free environment (Rogers et al., 2024). Furthermore, AI is being integrated into continuing professional development programs, helping practitioners stay updated with evolving diagnostic criteria, treatment guidelines, and research findings. Despite the clear advantages, the integration of AI into veterinary practice is not without challenges. First, data quality and availability remain significant hurdles, especially given the heterogeneity of species, breeds, physiological norms, and disease manifestations. AI models trained on limited or biased datasets may lack generalizability across species or geographic regions. Cross-species variability, in particular, complicates the validation and regulatory approval of AI tools for clinical use in veterinary medicine. There are also ongoing concerns related to data governance, privacy, and cybersecurity, particularly when integrating AI with cloud-based clinical information systems. Additionally, ethical considerations must be addressed regarding the transparency of AI decision-making (so-called "black box" algorithms), accountability in case of diagnostic errors, and the role of AI in replacing or augmenting human judgment. Moreover, the successful deployment of AI in veterinary settings requires interdisciplinary collaboration among veterinarians, computer scientists, data engineers, regulatory bodies, and industry stakeholders. Investment in infrastructure, training, standardization, and validation frameworks is critical to ensure that AI applications are safe, effective, and equitable. Veterinary professionals must also be equipped with the digital literacy necessary to interpret and critically evaluate AI-generated outputs.

3. Role of veterinary digital pathology in diagnosing infectious diseases in farm animals

Veterinary digital pathology has become a crucial tool for modern diagnosis and monitoring of infectious diseases in farm animals. By combining high-resolution whole-slide imaging (WSI), digital data management systems, and advanced artificial intelligence (AI)-based analysis tools, digital pathology enhances traditional histopathology methods, offering a more accessible, scalable, and efficient diagnostic platform. This technology greatly improves the detection and analysis of various bacterial, viral, and parasitic diseases that affect livestock health, productivity, and food safety.

One major benefit of digital pathology in veterinary diagnostics is its ability to capture and analyze complex tissue changes with exceptional detail and reproducibility. High-resolution slide scanning allows for the precise identification of tissue alterations linked to important diseases such as bovine tuberculosis (Elbarbary et al., 2024a), brucellosis (Diab et al., 2020), foot-and-mouth disease (FMD), bovine viral diarrhea (BVD), meat sarcocystosis (Elbarbary et al., 2025), and salmonellosis (Mahmoud et al., 2020). Using digital slide annotation, morphometric analysis, and standardized image interpretation, pathologists can better detect lesions associated with chronic inflammation, necrosis, granulomatous reactions, or protozoal cysts—key signs of these and other infectious diseases in farm animals.

A key advantage of digital pathology is its support for telepathology, which enables real-time remote diagnostic consultation between field veterinarians, laboratories, and reference centers. This feature is especially valuable in rural or resource-limited areas, where access to board-certified veterinary pathologists may be limited. Remote access to digital slides allows for faster diagnosis, which is critical in urgent situations needing immediate intervention to prevent herd transmission, economic losses, or public health risks (Abdel-Maguid et al., 2019). In addition, digital pathology plays an important role in epidemiological surveillance and outbreak management. Digitizing and centralizing diagnostic histopathological data help create integrated databases that support real-time disease monitoring, spatial mapping of disease spread, and retrospective studies. This standardized system helps veterinary public health agencies track the emergence or re-emergence of transboundary animal diseases and supports the development of evidence-based strategies for disease control at national and international levels.

The diagnostic capabilities of veterinary digital pathology are further improved when combined with molecular techniques. Merging digital histopathology with immunohistochemistry (IHC), in situ hybridization (ISH), and polymerase chain reaction (PCR) allows for accurate localization and identification of specific pathogens within tissues. For example, IHC can detect Brucella spp. antigens in placental tissues, while PCR confirms *Mycobacterium bovis* DNA in lymph nodes or lungs—significantly boosting diagnostic accuracy and confirming causative agents within altered tissues (Abo-Aziza et al., 2022). These multimodal diagnostics offer unmatched detail and reliability, especially in complex or multifactorial disease cases.

Beyond diagnosis, digital pathology is revolutionizing veterinary education and training. Digitally archived and annotated slides serve as valuable teaching resources, providing access to diverse case examples that might otherwise be limited by location or specimen access. These collections support interactive learning and standardized veterinary pathology curricula, especially through virtual microscopy platforms that simulate light microscopes (Fotouh et al., 2025).

In laboratory operations, digital pathology improves workflow efficiency and reduces costs by streamlining tasks traditionally limited by physical constraints. Automated slide scanning cuts down manual handling, while digital archives reduce the need for physical storage and eliminate risks of slide deterioration or loss. Moreover, AI-powered image analysis tools are increasingly capable of automating routine tasks like mitotic counts, lesion grading, and pathogen detection, freeing up pathologists to focus on more complex interpretive work (Turner et al., 2020).

Overall, veterinary digital pathology strengthens the ability to perform early, accurate, and scalable diagnoses of infectious diseases in farm animals. Its use promotes better animal health and welfare, reduces production losses, and enhances control of zoonotic pathogens that threaten public health (Fotouh et al., 2025). As veterinary pathology advances alongside digital and computational technologies, digital pathology will play an ever-growing role in a preventive, responsive, and data-driven approach to animal health aligned with the principles of One Health.

4. Role of Veterinary Digital Pathology in the Diagnosis of Different Diseases of Poultry

Veterinary digital pathology is revolutionizing the diagnosis, surveillance, and management of infectious diseases in poultry, a sector of critical global importance due to its central role in food security and the economy. As poultry production systems continue to scale, especially in low- and middle-income countries, the risk and complexity of managing infectious disease outbreaks grow proportionally. Diseases such as Newcastle disease, avian influenza, infectious bursal disease, avian leukosis (Elmeligy et al., 2024), reticuloendotheliosis, colibacillosis, salmonellosis, mycobacteriosis, and coccidiosis remain leading causes of morbidity and mortality in poultry flocks worldwide (Fotouh et al., 2020; Soufy et al., 2016; Shosha et al., 2024).

Traditional histopathological and microbiological diagnostic techniques, while foundational to veterinary pathology, are often constrained by logistical, temporal, and geographic barriers. These limitations are especially apparent in avian pathology, which requires the expertise of trained specialists to differentiate among diseases that present with similar or overlapping clinical and pathological features. For instance, lymphoid depletion is a common histological finding in several immunosuppressive viral diseases, and granulomatous inflammation may occur in both bacterial and parasitic infections. Consequently, timely and accurate differentiation is essential not only for clinical treatment but also for biosecurity and public health risk mitigation (Fotouh et al., 2024a).

Veterinary digital pathology addresses many of these limitations by enabling the digitization of tissue samples into high-resolution whole-slide images (WSIs), which can be analyzed, annotated, and shared remotely with avian pathologists and diagnostic laboratories globally (Diab et al., 2021; Zaki et al., 2025). This technology is particularly impactful in remote or under-resourced regions where access to avian pathology experts is limited. Through telepathology, digital slides can be reviewed rapidly, facilitating expert consultation and diagnostic confirmation in time-sensitive scenarios such as avian influenza outbreaks or Newcastle disease incursions, where swift intervention is crucial for containment.

Digital pathology also improves the resolution and fidelity of histopathological assessment, enabling detailed visualization of cellular and subcellular structures (Fotouh et al., 2025). This is particularly useful for characterizing bursal lesions in infectious bursal disease, lymphoid neoplasia in avian leukosis, or protozoal schizonts in intestinal epithelium during coccidial infections. Furthermore, the technology supports comparative pathology, allowing veterinarians to compare lesions across multiple birds or flocks, which is vital in identifying patterns of disease progression, severity, and response to treatment.

An increasingly important frontier in digital avian pathology is the integration of artificial intelligence (AI) and machine learning. These technologies are being developed to automate the recognition and quantification of specific histopathological features such as bursal atrophy, lymphocytic depletion, necrotic foci, and parasitic cysts. For example, AI algorithms can be trained to perform lesion scoring in coccidiosis and histomoniasis, providing objective, reproducible, and rapid assessments across large sample sets (Elbarbary et al., 2024b). This capability enhances epidemiological surveillance, supports research into vaccine efficacy and disease resistance, and allows for standardization in experimental and field-based pathology.

Moreover, digital pathology systems facilitate data centralization and interoperability, allowing diagnostic laboratories and veterinary institutions to contribute to shared repositories of annotated avian pathology cases. These databases are invaluable for large-scale epidemiological studies, meta-analyses, and the development of region-specific disease control strategies (Fotouh et al., 2024b). The ability to systematically collect and analyze digitized lesion data from multiple geographic locations accelerates the detection of emerging trends and facilitates timely policy responses.

In addition to diagnostics, digital pathology has a profound impact on veterinary education and training. Access to digital slide libraries allows veterinary students, pathology residents, and field practitioners to study a wide array of poultry diseases without the limitations imposed by physical specimens. This enhances the quality and accessibility of veterinary training globally, particularly in institutions that lack advanced histopathology infrastructure.

Operationally, digital pathology also enhances laboratory efficiency by reducing slide handling, minimizing degradation risks, and improving recordkeeping. Automated slide scanning and data archiving reduce turnaround times, streamline workflows, and lower costs over time by decreasing the reliance on physical storage and reprocessing of specimens (Salah et al., 2025a). Furthermore, digital systems support quality assurance by facilitating internal audits, external reviews, and retrospective analysis of archived cases.

5. Whole slide images (WSIS) and whole slide image scanners in veterinary digital pathology

Whole slide imaging (WSI), also known as virtual microscopy, is a foundational technology in digital pathology, enabling the digitization of conventional histological slides into high-resolution, interactive digital images. At the heart of this process are whole slide image scanners, advanced optical and mechanical devices designed to capture entire tissue sections on glass slides and convert them into comprehensive digital replicas with diagnostic quality (Zuraw and Aeffner, 2022).

A typical whole slide scanner utilizes high-precision robotic slide loaders, automated focus systems, and optical components comparable to those found in traditional light microscopes. Most scanners operate at 20x or 40x magnification, replicating or even exceeding the resolution seen through the eyepiece of a standard microscope (Ibrahim and Fotouh, 2024). Some high-end scanners offer z-stack imaging, allowing multiple focal planes to be captured and digitally reconstructed, which is particularly useful for thick tissue sections or cytological preparations. Advanced image acquisition systems in these scanners ensure uniform illumination, color consistency, and tissue fidelity, while autofocus algorithms dynamically adjust to variable tissue thickness across the slide, eliminating the common issue of focal drift. Scanning speed and throughput vary by model, with some high-capacity systems capable of scanning hundreds of slides in a single batch with minimal operator intervention (Pereira et al., 2023). The result is a high-fidelity, zoomable digital image that retains the essential histological and cytological details required for diagnostic interpretation.

Once digitized, WSIs can be stored in standardized image formats (e.g., SVS, NDPI, or DICOM), facilitating interoperability between platforms and software. Digital storage not only removes the logistical burden of physical slide archiving and transport but also protects against degradation, breakage, and loss. The digital nature of WSIs allows for instantaneous access, cloud-based archiving, and secure sharing between laboratories, educational institutions, and diagnostic centers globally (Luong, 2020).

In the context of veterinary pathology, the application of WSIs and scanners is particularly transformative. Veterinary pathology encompasses a wide range of species and tissue types, often requiring consultation with subspecialists in exotic or production animals. Through WSI-based telepathology, digital slides can be reviewed by remote experts, enabling rapid second opinions and diagnostic support in regions lacking in-house pathology services. This is especially valuable in large-scale animal health investigations, zoonotic disease surveillance, and outbreak response scenarios.

WSIs are also central to veterinary education and training. Digital slide libraries provide students and residents with access to diverse case materials and rare pathologies that may not be routinely available in local teaching collections. Interactive tools embedded in WSI viewing software allow for annotations, measurements, and collaborative review sessions, enriching the learning experience and supporting standardized pathology curricula. Moreover, the integration of WSIs with AI and machine learning systems has enabled the development of powerful diagnostic support tools. These tools can analyze entire slides or selected regions of interest to detect, classify, and quantify lesions, cellular patterns, mitotic figures, or pathogen inclusions. Such AI-enhanced systems not only improve diagnostic efficiency and reproducibility but also enable high-throughput screening and research applications in comparative pathology, toxicologic pathology, and infectious disease surveillance.

Despite these advantages, the adoption of WSI in veterinary pathology is not without challenges. High-resolution imaging generates large file sizes (often several gigabytes per slide), necessitating robust data storage infrastructure, high-speed internet connectivity for telepathology, and secure data handling protocols to ensure confidentiality and data integrity. In addition, validation studies are needed to confirm that diagnoses rendered on WSIs are equivalent to those made by traditional light microscopy, particularly for species with unique tissue characteristics.

Nevertheless, the combination of whole slide images and whole slide scanners is rapidly redefining how pathology is practiced, taught, and applied in both clinical and research domains. As costs decline and digital infrastructure improves, WSI is expected to become an indispensable component of modern veterinary diagnostic workflows, facilitating greater global collaboration, enhancing educational resources, and unlocking new opportunities in AI-assisted diagnostic technologies (Rogers et al., 2024).

6. Machine learning and artificial intelligence applications on whole slide images in veterinary pathology

The integration of machine learning (ML) and artificial intelligence (AI) with whole slide images (WSIs) represents one of the most transformative developments in digital pathology, offering unprecedented opportunities for the automated analysis, interpretation, and classification of complex tissue structures. As veterinary pathology encompasses a wide range of species and disease processes, the application of AI to WSIs is poised to revolutionize diagnostic workflows, improve consistency, and enhance both research and educational efforts in the field (Pereira et al., 2023).

AI systems, particularly those leveraging deep learning algorithms such as convolutional neural networks (CNNs), are capable of processing high-resolution WSIs to perform a variety of tasks that historically required expert human interpretation. These include tissue segmentation, feature extraction, classification of histopathological patterns, and detection of rare or subtle lesions that may be overlooked during manual evaluation (Luong, 2020). For example, deep learning models can accurately delineate tumor boundaries, identify mitotic figures, assess lymphocytic infiltration, and quantify fibrotic or necrotic regions in neoplastic, infectious, or degenerative disease contexts (Fotouh et al., 2025).

In veterinary pathology, AI algorithms can be trained on annotated WSIs from various animal species to support the diagnosis of a broad spectrum of diseases, ranging from lymphoma in dogs to avian leukosis in poultry and granulomatous lesions in tuberculosis-infected cattle. The development of multi-species AI models is particularly valuable, as veterinary pathology involves a much greater biological diversity than human pathology, requiring adaptable algorithms capable of interpreting interspecies variation in tissue architecture and cellular morphology (Amaral et al., 2024). Moreover, AI tools are increasingly being used for quantitative image analysis, allowing for the objective measurement of diagnostic features such as lesion area, cell density, vessel proliferation, and mucin content, among others. These measurements can be standardized across laboratories and studies, promoting reproducibility and reducing inter-observer variability, which has long been a challenge in traditional pathology (Zuraw and Aeffner, 2022). Quantitative metrics derived from WSIs can also be integrated with clinical and molecular data for multi-modal analyses, which improve our knowledge of disease pathogenesis and treatment response.

Another major advantage of ML-based systems is their potential to triage cases based on urgency or diagnostic complexity. For instance, AI algorithms can be trained to rapidly screen incoming WSIs for features suggestive of malignancy, infection, or other high-priority findings, flagging them for immediate review by a pathologist. This triaging capability enhances workflow efficiency, especially in high-volume diagnostic centers or during outbreak investigations where timely diagnosis is critical for disease control and herd management (Ibrahim and Fotouh, 2024).

As AI models are exposed to larger and more diverse image datasets, they undergo continuous improvement through iterative training, validation, and testing. This process enhances their robustness and generalizability, ensuring their applicability to a wide array of tissue types, staining protocols, and imaging conditions. Furthermore, the advent of explainable AI (XAI) is addressing the need for transparency and interpretability in AI-driven diagnostics, allowing pathologists to understand the basis for algorithmic decisions and integrate them with human judgment in a collaborative diagnostic model.

Despite these advancements, several challenges must be addressed for the widespread adoption of AI in veterinary digital pathology. These include the need for species-specific validation, standardization of slide scanning protocols, curation of annotated datasets, and ethical considerations related to algorithm bias and decision-making autonomy. Ensuring the quality and consistency of training data is particularly critical, as the performance of AI models depends heavily on the accuracy and representativeness of the ground truth annotations provided by expert pathologists. In research settings, AI-WSI platforms enable high-throughput histological analysis in large-scale studies, such as vaccine trials, toxicological assessments, and phenotypic characterization of genetically modified animals. In education, AI-augmented WSIs can provide interactive learning tools, offering real-time feedback and automated assessments of diagnostic accuracy for veterinary students and pathology trainees.

Nevertheless, the integration of AI and ML technologies with WSIs is set to redefine the landscape of veterinary pathology. These tools promise to augment the diagnostic capabilities of pathologists, streamline clinical workflows, enable new forms of research and education, and ultimately contribute to the advancement of precision veterinary medicine within the broader framework of One Health (Turner et al., 2020).

6. Veterinary digital pathology and image analysis

Veterinary digital pathology represents a transformative advancement in diagnostic veterinary medicine, particularly in the field of image analysis, where the transition from analog to digital systems has fundamentally altered how pathological data is acquired, analyzed, and interpreted. By enabling the digitization of histological slides through whole slide imaging (WSI), veterinary digital pathology allows for high-resolution, navigable digital replicas of tissue sections that can be stored, reviewed, annotated, and analyzed with computational tools (Aeffner et al., 2021).

The ability to digitize and computationally examine slides facilitates precise and reproducible image analysis, a process that is especially valuable in veterinary medicine due to the broad diversity of species and tissue morphologies encountered in practice. Using advanced image analysis software often integrated with artificial intelligence (AI) and machine learning (ML) algorithms, veterinary pathologists can perform quantitative assessments of histological features that were traditionally evaluated subjectively under a light microscope (Amaral et al., 2024). These features include cell density, mitotic index, tumor grading, necrotic area quantification, inflammatory infiltrate assessment, and distribution of infectious organisms, among others.

Such analyses not only reduce inter- and intra-observer variability but also support the development of standardized diagnostic protocols, which are especially critical in veterinary settings where access to species-specific expertise and reference datasets may be limited. For example, objective quantification of lymphoid depletion in avian bursa or granulomatous lesions in ruminant lungs can improve diagnostic consistency across institutions and geographic regions. Moreover, in complex disease presentations—such as multifactorial infections in poultry or concurrent neoplastic and infectious conditions in companion animals—automated image analysis can assist in differentiating overlapping histopathological features, thereby supporting more accurate diagnoses (Brown et al., 2016).

One of the most promising applications of image analysis in veterinary digital pathology lies in its integration with AI-based detection and classification algorithms. These tools can be trained to recognize patterns in digitized tissue sections and execute tasks such as tumor boundary segmentation, identification of parasitic cysts, scoring of coccidial lesions, and detection of viral inclusion bodies, often with accuracy approaching that of expert pathologists. In research contexts, such as preclinical toxicology studies or vaccine efficacy trials, AI-driven image analysis enables high-throughput, reproducible, and unbiased histological assessments, significantly reducing the time and labor required for manual slide evaluation (Zuraw and Aeffner, 2022).

Digital pathology platforms also offer significant advantages in longitudinal and comparative studies, where sequential tissue samples collected over time or from different populations can be analyzed using consistent image processing algorithms. This ensures temporal consistency in data analysis and facilitates statistical modeling of disease progression, treatment response, or pathogen distribution. Such capabilities are invaluable in veterinary epidemiology, herd health monitoring, and the study of zoonotic disease dynamics. Furthermore, the scalability of digital pathology and automated image analysis makes them ideal for disease surveillance programs, enabling rapid review of large volumes of tissue samples, early outbreak detection, and informed decision-making in animal health management. This is especially pertinent in the monitoring of high-impact transboundary animal diseases such as avian influenza, foot-and-mouth disease, and bovine tuberculosis, where timely diagnosis is essential for containment and mitigation.

Despite its many advantages, the adoption of digital pathology and automated image analysis in veterinary settings faces technical and infrastructural challenges. These include the need for standardization of scanning protocols, validation of algorithms across different species and tissues, high-performance computing resources, and secure data storage solutions. In particular, the development of accurate and generalizable AI models depends heavily on access to large, annotated veterinary WSI datasets, which remain limited compared to human pathology.

Nonetheless, the integration of digital pathology with image analysis technologies continues to drive precision veterinary diagnostics, improve laboratory efficiency, and contribute to evidence-based veterinary medicine. As computational tools become more sophisticated and widely accessible, their role in advancing animal health, supporting public health initiatives, and bridging gaps in global veterinary care will only expand.

7. Integration of veterinary telepathology and digital pathology with artificial intelligence

The convergence of veterinary telepathology, digital pathology, and artificial intelligence (AI) is reshaping the diagnostic framework of veterinary medicine, offering a paradigm shift in how animal diseases are detected, monitored, and managed across species and geographies. This integration facilitates a more rapid, scalable, and accurate diagnostic workflow, particularly valuable in addressing the challenges of disease surveillance and control in a One Health context (Rogers et al., 2024).

Veterinary digital pathology begins with the conversion of traditional histopathological slides into high-resolution whole-slide images (WSIs) using advanced slide-scanning systems. These digital formats preserve the morphological integrity of tissue samples and enable seamless storage, annotation, and retrieval (Battazza et al., 2024). When paired with telepathology, the remote review and consultation of digitized histological material by veterinary pathologists, this technology extends diagnostic capabilities to under-resourced and geographically isolated settings, addressing the global disparity in access to veterinary specialists.

Telepathology platforms enable real-time consultations between local clinicians and international experts, ensuring timely and informed diagnostic interpretations. This is especially critical in situations such as zoonotic disease outbreaks, mass animal morbidity events, or biosecurity threats, where swift decision-making can significantly influence outcomes in both animal and human populations. By transcending physical and logistical barriers, telepathology promotes collaborative diagnostics, enhances continuity of care, and supports interdisciplinary partnerships among veterinarians, epidemiologists, and public health professionals.

The incorporation of AI into digital telepathology workflows further amplifies diagnostic efficiency and precision. AI algorithms, particularly those based on deep learning, are capable of rapidly analyzing WSIs to detect and quantify pathognomonic features such as cellular atypia, lesion architecture, pathogen morphology, and inflammatory infiltrates. These tools can be trained to recognize species-specific and disease-specific patterns, enabling highly accurate classification of neoplastic, infectious, parasitic, and inflammatory conditions in companion animals, livestock, poultry, and wildlife (Amaral et al., 2024).

A key application of AI in this context is triaging large volumes of digital slides, flagging those with urgent or suspicious findings for immediate pathologist review. This not only accelerates workflow but also reduces the diagnostic burden on overextended pathology services, particularly in high-throughput environments such as farm animal diagnostic labs or national veterinary surveillance programs (Bouchemla et al., 2023). Early AI-assisted detection of diseases such as avian influenza, bovine tuberculosis, brucellosis, and salmonellosis can significantly mitigate morbidity, mortality, and economic losses associated with delayed intervention (Sadek et al., 2024). Moreover, this integrated ecosystem supports the development of centralized digital pathology repositories—comprehensive, cloud-based archives of annotated WSIs from diverse animal species and disease states. These repositories are invaluable for longitudinal epidemiological studies, comparative pathology research, and veterinary education (Brown et al., 2016). AI-driven data mining and pattern recognition across such datasets can uncover emerging disease trends, geographic hotspots, and novel pathological associations that would be challenging to detect through conventional analysis.

For veterinary educators and students, the availability of AI-augmented digital case libraries enhances learning by offering access to a wide range of pathology specimens from various species, complete with diagnostic annotations, virtual assessments, and decision-support tools (Luong, 2020). These resources democratize education, allowing learners from all regions to engage in high-quality, interactive pathology training without the need for physical slide sets or laboratory infrastructure.

Despite its transformative potential, the integration of digital pathology, telepathology, and AI also presents several challenges. These include the standardization of imaging protocols, interoperability of software systems, data privacy and cybersecurity, and the validation of AI algorithms across species with diverse anatomical and histological characteristics. Regulatory and ethical frameworks must evolve to ensure responsible deployment, particularly in clinical decision-making contexts where diagnostic errors can have significant consequences for animal welfare and public health.

Nevertheless, the synergistic integration of these technologies marks a critical evolution in veterinary diagnostics and global health preparedness. By enabling real-time, expert-driven, AI-enhanced diagnostics, this model supports early disease detection, facilitates faster treatment initiation, promotes an efficient outbreak response, and enhances animal health outcomes, while also contributing to food security and the prevention of zoonotic diseases. As digital infrastructure and AI models continue to advance, the full realization of this integrated approach will likely redefine the future of veterinary medicine on a global scale (Piccione et al., 2025).

8. Implementing digital pathology into veterinary academics and research

The implementation of digital pathology in veterinary academics and research represents a transformative advancement that is reshaping how veterinary medicine is taught, investigated, and applied in both clinical and scientific contexts. Digital pathology involves the digitization of histological glass slides through high-resolution scanners to produce whole slide images (WSIs), which can be viewed, analyzed, stored, and shared electronically (Battazza et al., 2024). This technological evolution has opened new avenues for veterinary institutions by enhancing educational quality, promoting collaborative research, and supporting more efficient diagnostic practices (Bertram and Klopfleisch, 2017).

8.1. Enhancing veterinary education

In veterinary education, digital pathology offers a flexible and innovative platform for teaching histopathology—an essential component of veterinary curricula. Traditional teaching methods relying on light microscopy and physical slide sets are often hindered by logistical issues, including slide degradation, limited access during in-person sessions, and variability in slide quality that may affect learning outcomes (Bertram and Klopfleisch, 2017). Digital slides largely overcome these limitations by providing standardized, high-quality image libraries accessible to students anytime and anywhere, facilitating both classroom and remote learning. The COVID-19 pandemic accelerated the adoption of such digital tools, highlighting their importance in flexible education delivery (Piegari et al., 2018). Interactive platforms now allow students to annotate, zoom, and navigate slides, replicating the traditional microscope experience with added convenience and scalability (Brown et al., 2016).

8.2. Advancing veterinary research

From a research standpoint, digital pathology enhances data integrity, reproducibility, and workflow efficiency. Researchers benefit from the ability to store and catalog thousands of digital slides, enabling seamless longitudinal studies and retrospective analyses (Ibrahim and Fotouh, 2024). High-resolution WSIs allow for precise morphometric assessments, automated quantification, and integration with other biological datasets such as genomics and proteomics (Bertram and Klopfleisch, 2017). Additionally, digital pathology forms the foundation for incorporating AI and machine learning into veterinary research. By training algorithms on extensive annotated image datasets, researchers can automate the detection of histological features, lesion classification, and disease marker identification, accelerating research progress and reducing manual workload. AI-powered digital pathology also holds promise in comparative pathology, facilitating translational insights between veterinary and human medicine (Piccione et al., 2025).

8.3. Fostering global collaboration

Digital pathology also supports global collaboration and knowledge exchange in veterinary research. Through telepathology, institutions can consult international experts, share case studies, and engage in multicenter studies without the logistical challenges of physical slide transport (Piegari et al., 2018). This connectivity is particularly vital for rare diseases or exotic species, where access to specialized pathology expertise is limited. It further enhances professional development by enabling virtual case rounds, workshops, and continuing education programs accessible worldwide (Turner et al., 2020).

8.4. Challenges and considerations

Despite its advantages, implementing digital pathology in veterinary academia and research faces several challenges. High upfront costs for slide scanners, data storage infrastructure, and specialized analysis software pose barriers, particularly for resource-limited institutions (Webster et al., 2014). Ensuring data security, standardizing digital slide formats, and developing robust guidelines for digital image analysis are essential considerations. The integration of AI requires large, well-annotated datasets and rigorous validation across multiple species and disease types—tasks that are resource- and time-intensive. Moreover, effective faculty training and change management strategies are necessary to facilitate the transition from conventional microscopy to digital workflows (Webster et al., 2014; Salah et al., 2025).

8.5. Future outlook

Despite these challenges, the long-term benefits of digital pathology in veterinary education and research are significant. It fosters a more dynamic and interactive learning environment, enables cutting-edge scientific discovery, and strengthens global veterinary collaboration. As technology continues to advance and become more accessible, digital pathology is poised to become an integral part of veterinary academia, enhancing educational experiences, improving research outcomes, and fostering greater integration between veterinary and biomedical sciences (Jones-Hall et al., 2022).

9. Importance of pathology informatics in the digitization of veterinary pathology

Pathology informatics plays a core role in the digitalization of veterinary pathology because it is the underlying framework that integrates the data acquisition, management, analysis, and communication of digital pathology workflows. As veterinary pathology progresses from traditional microscopy to WSI and AI-assisted diagnostics, pathology informatics facilitates effective processing of large volumes of complex data generated through high-resolution imaging and multi-modal clinical data sets (Kusta et al., 2022). The informatics infrastructure provides storage, recall, and secure dissemination of digital slides and associated metadata among geographically distant institutions, circumventing the past limitations of physical slide transport and specialist availability. Pathology informatics also allows for standardization and interoperability of imaging modalities and diagnostic annotation, critical in the creation and testing of effective AI algorithms that require large sets of well-curated and annotated examples (Volynskaya et al., 2018). Aside from image management, informatics systems provide the ability to combine histopathological findings with other clinical and molecular data for the support of specific diagnostics and tailored veterinary therapy (Gabril and Yousef 2010). Informatics tools also provide novel arenas for telepathology, remote consultancy, and collaborative research, providing pathways to specialist knowledge in species- and tissue-type pathology areas often underserved in the field of veterinary medicine. Pathology informatics implementation also includes required regulatory and ethical necessities through the imposition of data security, patient confidentiality, and audit trails for clinical accreditation and compliance (Joseph 2015).

10. Uses of computer vision technologies in veterinary pathology

Computer vision algorithms have become increasingly core to veterinary pathology, with state-of-the-art solutions for automatic analysis and interpretation of complex histopathological images. By leveraging algorithms to enable machines to "see" and understand visual data, computer vision enables the quantitative and qualitative data to be extracted from WSIs with outstanding precision and speed (Fernandes et al., 2020). In veterinary pathology, where tissue diversity and species pose unique diagnostic challenges, computer vision software optimizes and standardizes the analysis of morphological features such as tissue pattern, cellular structure, and pathological conditions, including tumors, inflammation, and infectious agents. Techniques such as image segmentation, feature extraction, and pattern recognition can allow for accurate identification and classification of cellular structures, mitotic figures, necrotic areas, and other diagnostic features that traditionally require expert interpretation by a microscope (Smith et al., 2024). In addition, computer vision in combination with deep learning models, in particular convolutional neural networks (CNNs), can learn to recognize subtle histopathological patterns in large datasets with a tendency to exceed human observers in consistency and speed. This technology also supports quantitative measurements such as tumor grading, fibrosis scoring, and inflammatory cell counting, resulting in objective and reproducible diagnostics. Furthermore, computer vision enables telepathology applications through supporting real-time remote slide analysis and decision support, which is critical in veterinary settings where access to specialist pathologists is limited (Sandberg et al., 2023). Beyond diagnostics, computer vision assists research via high-throughput tissue microarray analysis, biomarker discovery, and longitudinal monitoring of disease progression in a range of animal species. Continued innovation of increasingly sophisticated computer vision algorithms promises to automate veterinary pathology workflows, enhance diagnostic confidence, and support personalized treatment strategies by providing precise, reproducible, and scalable image analysis solutions accommodating the intricacies of veterinary medicine (Burrai et al., 2023).

11. Challenges and future direction of veterinary digital pathology

Despite its transformative potential, veterinary digital pathology faces several challenges that must be overcome to ensure its successful and widespread adoption. One of the foremost obstacles is the high cost of implementation. The acquisition of whole slide scanners, data storage solutions, image management software, and the necessary IT infrastructure can be prohibitively expensive, particularly for smaller clinics, research institutions, and universities in developing regions (Piccione et al., 2025). Additionally, the lack of standardized protocols for slide scanning, image formatting, and digital workflows across veterinary institutions hampers interoperability and efficient data sharing (Webster et al., 2014).

Another critical challenge lies in the limited availability of large, annotated datasets from diverse animal species. Such datasets are essential for training and validating AI algorithms that enhance diagnostic accuracy and enable automated analysis. Unlike human pathology, veterinary digital pathology must address the complexities of species diversity, a wide range of disease presentations, and the absence of centralized digital repositories (Piegari et al., 2018).

Furthermore, there is a pressing need for training programs aimed at familiarizing veterinary pathologists, clinicians, and students with digital pathology tools and AI-driven platforms. Resistance to change and unfamiliarity with digital workflows may slow adoption. Concerns related to data privacy, storage security, and archival standards also require careful consideration, especially when managing sensitive diagnostic information.

Despite these challenges, the future outlook for veterinary digital pathology remains highly promising (Webster et al., 2014). Advances in technology are driving down the costs of scanners and infrastructure, while cloud-based platforms are helping overcome geographical and resource constraints. Collaborative initiatives to establish open-access digital slide libraries and shared multi-species databases are progressing, which will accelerate AI development and refine diagnostic tools (La Perle, 2019).

As digital literacy grows and the benefits of digital pathology—such as enhanced remote consultation, improved education, faster and more accurate diagnostics, and expanded research capabilities—become increasingly evident, its integration into routine veterinary practice and academia is expected to expand substantially (Luong, 2020). The future will likely see deeper integration of AI, real-time diagnostics through telepathology, and enhanced global collaboration, building scalable, robust systems to advance animal health care, education, and research worldwide (Ibrahim and Fotouh, 2024).

Conclusion

Veterinary digital pathology is revolutionizing the field of animal health by bridging traditional diagnostic methods with cutting-edge technology. Through high-resolution digitization, remote access, AI-driven analysis, and collaborative platforms, it enhances diagnostic accuracy, research efficiency, and educational outreach. While challenges related to cost, standardization, data management, and training remain, ongoing technological advancements and collaborative efforts are paving the way for its broader adoption. The integration of digital pathology into veterinary medicine promises not only to improve animal health and productivity but also to foster global connectivity and innovation within the veterinary and biomedical sciences, ultimately contributing to the advancement of One Health initiatives.

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