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TRANSFORMATIVE TECHNOLOGIES FOR THE FUTURE OF CAMEL WELFARE: ARTIFICIAL INTELLIGENCE FOR IMPROVED DIAGNOSTICS, THERAPEUTICS AND HEALTH OUTCOMES

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ABSTRACT

This review explores the innovative application of Artificial Intelligence (AI) in advancing camel health and welfare. It investigates the utilisation of various AI methodologies, including supervised learning, unsupervised learning, reinforcement learning, and Deep Learning techniques such as Convolutional Neural Networks (CNNs), specifically tailored towards the healthcare management of camels. The review highlights significant advancements in AI for early disease detection, diagnosis, treatment, and monitoring in camels, showcasing its pivotal role in precision medicine, automated disease diagnosis, and the optimization of treatment protocols. Notably, AI is effective in evaluating the toxicological impact of chemical substances, enhancing diagnostic accuracy through image-based diagnostics, and facilitating the early prediction of diseases like *Trypanosoma evansi* using artificial neural networks. Furthermore, AI contributes to the development of camel-derived diagnostic and therapeutic products, emphasising the utility of Machine Learning in analysing complex datasets for antibodies and nanobodies discovery and optimisation. Additionally, the application of AI in camel management and welfare, including weight prediction and the assessment of camel milk adulteration, illustrates the technology's broader implications. The findings indicate that AI not only significantly enhances the accuracy and efficiency of camel healthcare and welfare but also opens new avenues for research and development in the domain of camelids. The study calls for further AI applications to fully harness AI's potential in revolutionising camel healthcare and welfare practices, especially in the tracks of camel diseases treatment and control.

Key words: Artificial intelligence, camel, diagnosis, healthcare, machine learning

Varying climate conditions in different geographic locations including Africa's deserts have a great influence on the production of the food and also how much food is consumed especially from camel sources (Boudalia *et al,* 2023). Traditionally used as a means of transportation, camels are now an essential food source for inhabitants of semiarid and desert areas. Owing to their inherent versatility and adaptability to survive in harsh environmental conditions, camels are successfully bred in both hot and cold climates (Koç, 2022) and fulfill the demand for milk and meat in both traditional camel-raising regions and Western countries (Faye, 2018; 2020). Camels are regarded as the animals of the future because of their extraordinary adaptability in varying climate conditions (Ashour and Abdel-Rahman, 2022). In addition, camel milk has proved unique efficiency in modulating and treating various human diseases (Kandeel, 2022).

Compared to other farm animals, camels get less attention from researchers and are subject to certain standards similar to those of cattle despite several differences. For instance, camel calves are reared on the same type of concentrated food just like cattle calves and milked with the aid of machines and ear tags designed for cattle. Each year, more than three million tons of milk and 600,000 tons of meat have been produced by almost 40 million camels. The number of camels surged 3.05 times more over 1961-2021 compared to poultry and goats. Camels produced roughly five times as much meat and milk within that period (FAO, 2022).

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It is particularly challenging to apply knowledge and technologies created for cattle or other livestock species to camels and advancements in camel products since camels are primarily raised in areas where technological advancements have arrived much later and because camels and its products differ significantly from other farm animals (Baig *et al,* 2022; Gerdan Koc *et al,* 2024). Thus, it is necessary to dig deeper into scientific knowledge and design new techniques specific to camels. Moreover, diagnosis and treatment methods for camel diseases also need special attention as most of the countries where camels are reared are underdeveloped. These countries have a shortage of expert veterinarians specialised in camel disease diagnosis and treatment. This may result in incorrect diagnosis, delayed therapy, and poor efficiency of medications. The lack of standardisation and accessibility of diagnostic testing kits is a significant obstacle to accurately diagnosing camel diseases. In terms of treatment methods, optimised treatment regimens are still lacking due to very little research on camels. Scientists are using computational tools and techniques such as Artificial intelligence (AI) to conduct robust research and design new diagnostic tools and treatment methods specific to each individual (Kour *et al,* 2022).

The term "artificial intelligence" refers to the intelligence exhibited by machines or computer systems that can be used to do various tasks through the use of Natural Language Processing (NLP) and sentiment analysis. With the use of this technology, machines can comprehend the information given as well as acquire previous data on their own (Bouhali *et al,* 2022). These tools can then use this information to perform a variety of functions. Machine Learning and Deep Learning are subsets of AI, and each of these technologies has specific tasks when it comes to computing technology. AI has several benefits over conventional analytics and clinical decision-making techniques (Bohr and Memarzadeh, 2020a; Kour *et al,* 2022). In this regard, the present study has reviewed the results of the latest studies that used AI techniques in the domain of camel welfare and health.

Fig 1 shows the application of various AI domains such as Machine Learning, Deep Learning, Robotics, Speech Recognition, and NLP to the field of camel care and products. It illustrates a transition from the conceptual representation of AI as a digital brain to specific uses in camel-related contexts, with applications in disease diagnosis, healthcare, the detection of adulteration in camel products, and the development of camel-derived therapeutic products, aiming to improve management and welfare practices for camels.

Artificial intelligence in public healthcare and animal welfare sectors

Digitised approaches in the healthcare sector can provide error-free outcomes, reducing the frequency of human error. Various AI-based approaches like supervised learning, unsupervised learning, and reinforcement methods can provide a better understanding of the diseases, their data collection, and initial diagnosis (Abedi *et al,* 2020).

Notable advancements and potential development, use, and clinical integration of AI in the healthcare system of humans and animals have opened new ways for disease diagnosis and treatment. AI has shown promising results in human healthcare as it helps advance the area of precision medicine, which tailors treatment depending on genetic differences between the individuals and other variables, as well as for research and discovery of new drug candidates (Davenport and Kalakota, 2019). In the field of substances safety profiles, a Machine Learning-based program DeepTox evaluates the harmful impacts of chemical substances of drug molecules in image-based diagnostics (Bohr and Memarzadeh, 2020b; Mayr *et al,* 2016). The Tox21 Data Challenge assessed computational methods for toxicity prediction, involving 12,000 chemicals across 12 toxic effects. Deep Learning was investigated for its potential in this domain, leveraging its ability to create abstract representations of chemical features. The DeepTox pipeline, developed for this purpose, normalized chemical representations, computed descriptors, trained models, and predicted toxicity. DeepTox outperformed other methods in the challenge, showcasing the effectiveness of Deep Learning in toxicity prediction.

When it comes to solving problems related to animal health, Deep Learning is an effective tool for identifying patterns and signals, comprehending the dynamics of disease transmission, and generating computer-based decisions. The human health industry is currently using this technology, which has been developed since the 1980s (Ezanno *et al,* 2021). However, not much work has been done on the animal health sector. AI can be a useful technology to address the challenges faced by animal health sectors by evaluating the collected data on animals, infections, and their surrounding environment. Improvements in risk analysis, disease diagnosis, and individual case detection have been made possible

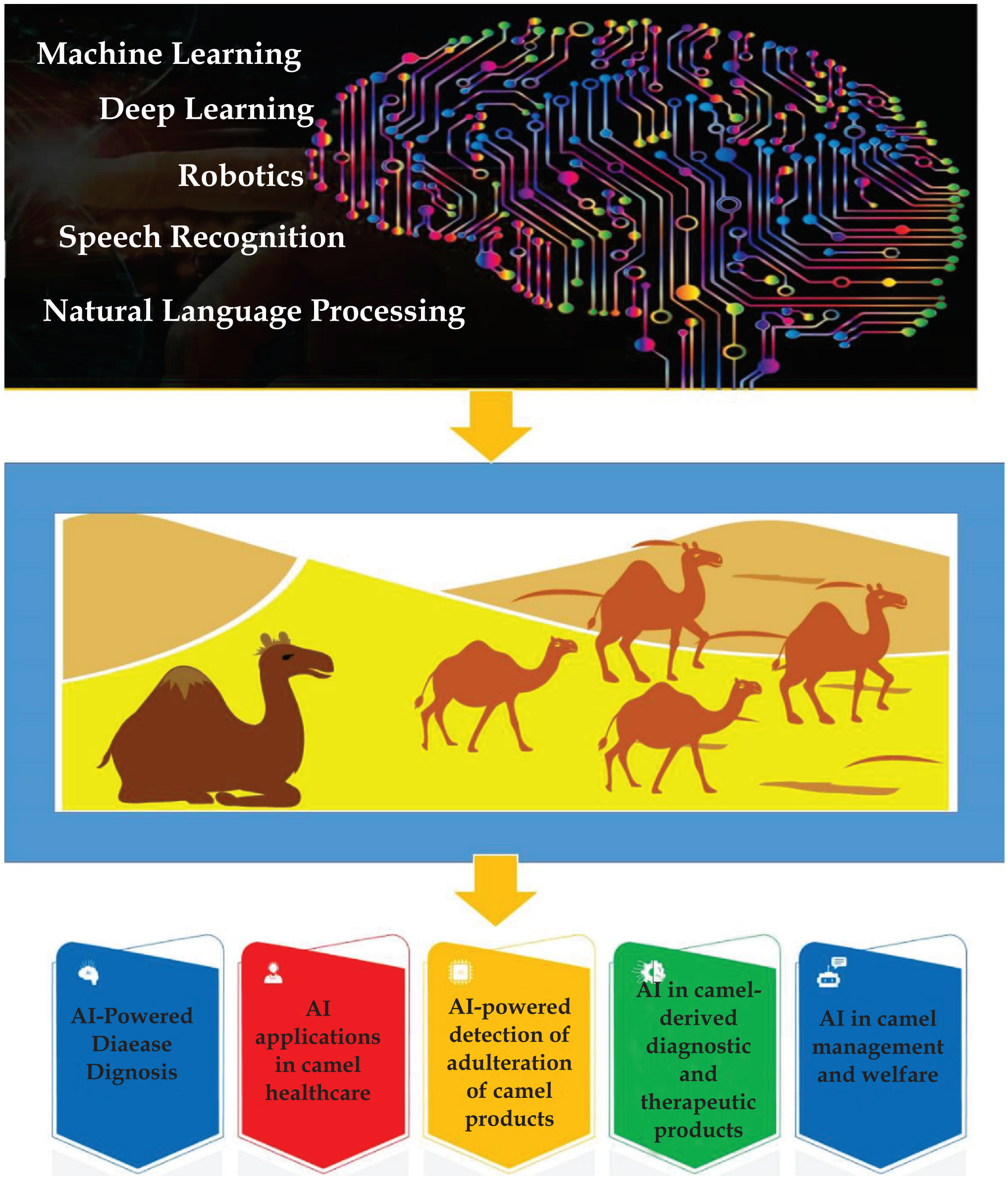

Fig 1. The various domains and applications of AI in camel welfare and healthcare. The figure is generated by using the slide team tools licensed to the corresponding author.

by developments in Machine and Deep Learning techniques (Karczewski and Snyder, 2018; Saria *et al,* 2018).

Using CNNs has demonstrated potential to enhance various diagnostic procedures within veterinary medicine. Specifically, it has effectively identified lung irregularities in feline radiographic images. This technology could significantly enhance the precision of diagnoses and the decision-making workflow in veterinary settings (Dumortier *et al,* 2022).

An emerging field of interdisciplinary study is concentrating on the intersection of Deep Learning and animal welfare. Several instances were investigated in this context, comprising automated bird count using Deep Learning (Akçay *et al,* 2020) and action recognition using a Spatial-Temporal Network for wild felines (Feng *et al,* 2021). Contemporary AI techniques are being applied to scientifically assess and evaluate the well-being of animals through the examination of extensive datasets encompassing information on animal physiology, behaviour, and health data.

The pivotal role of AI tools in automated animal activity recognition (AAR), highlighting their significance in monitoring animal behaviour in real-time was extensively discussed (Mao *et al,* 2023). Recent strides in sensing technologies and smart computing have propelled significant advancements in AAR research. AAR using wearable sensors and Deep Learning techniques is essential for precise animal monitoring and management, offering insights into animal health and welfare and guiding care actions and environmental enhancements.

AI-powered continuous surveillance ensures at-risk patients receive ongoing observation, which facilitates the faster detection of shifts in disease biomarkers. This is especially beneficial for chronic medical conditions as it allows patients to receive proactive care with prompt treatment. A machine-learning system has reportedly been used to identify chronic hypoadrenocortism (CHA) in dogs. Due to inadequate understanding and a low level of suspicion, diagnosing CHA can be quite difficult. Using regularly recorded screening information of biomarkers including a serum chemical profile and complete blood count, Machine Learning algorithms were used to diagnose the CHA (Reagan *et al,* 2020). Similarly, canine glial cell neoplasia and non-infectious inflammatory meningoencephalitis have been distinguished using Texture Analysis (TA). Even for experienced diagnostic imaging professionals, this procedure might be extremely challenging to do due to overlapping image attributes (Wanamaker *et al,* 2021). In order to improve sensitivity, precision, and repeatability, attempts are currently being made to use radionics and AI as tools for assisting decision-making and integrate these technologies into routine clinical procedures and diagnostics (Bohr and Memarzadeh, 2020b).

AI-Powered Disease Diagnosis for Camels

Detection of any disease in its early stages can provide a better understanding and look for possible treatment options against that specific ailment. Therefore, taking rapid action with the available data can be of substantial value in developing effective possible solutions (Kumar *et al,* 2023).

A study was conducted in 2022 for the early prediction of *T. evansi* in 115 camels utilising ANNs. *T. evansi* is responsible for causing Surra, which is a severe yet neglected disease affecting camels. An immune trypanolysis test was conducted to check the production of their effective antibodies. Various elements, like age, gender, herd size, clinical history, etc., were considered as the predicting parameters of the infection. Later, an ANN was employed to test the accuracy of the predicted input parameters as the diagnostic tools of the disease. The study's results suggested that the Tansig transfer function effectively predicted the diagnostic parameters of *T. evansi* and, therefore, can be effectively utilised by veterinarians for early prediction of the disease in dromedaries (Benfodil *et al,* 2022).

The gut microbiome can also serve as a valuable marker for diagnosing various camel diseases. A very recent study was conducted to assess the camel gut microbiome and its association with multiple parameters as a diagnostic tool. Almost fifty-five camels were included in the survey, whose gut microbiome analysis was carried out using the metagenomic shotgun sequencing approach of the Fathi Camel Microbiome Project. The analysis showed substantial microbial diversity patterns, which helped establish a massive collection of Prokaryotic Metagenome Assembled Microorganisms that can serve as a reference microbiome profile. Random forest package, which is a Machine Learning tool, was used to analyse the relationship between various parameters and the microbiome. The correlation of the microbiome with the dietary component, specifically wheat consumption, revealed that the microbiome profile of camels has notable associations with diet patterns. Therefore, it was assessed that gut microbiome association with various physical parameters can be a diagnostic tool (Mubaraki, 2024).

AI holds the promise to transform animal healthcare, revolutionising veterinary services and enhance the well-being of animals. A leading area within healthcare, known as radiomics, leverages complex mathematical models to quantitatively analyse results from medical imaging. This suggests that imaging data hold insights into disease mechanisms that are beyond human visual detection (Mao *et al,* 2023). Radiomics involves analysing a vast array of medical images and modalities, requiring AI for handling the extensive data and extracting features suited for AI algorithms, blending radiomics and AI in diagnostics. The evolution of AI, particularly Deep Learning, has significantly enhanced diagnostic systems across all imaging types, with Deep Learning minimising the need for manual preprocessing and segmentation. CNNs, are notably effective, comprising layers for feature detection, selection, and integration for image classification (Mao *et al,* 2023). Radiomics integrates advanced image analysis in veterinary medicine, offering insights beyond traditional imaging by using standardised methods to analyse multi-dimensional images for correlations with genetic and pathological data. It provides both visible and non-visible features for analysis, enhancing diagnostics, prognosis, and treatment planning (Basran and Porter, 2022).

AI-powered detection of adulteration of camel products

Camel milk is known for its high nutritional composition and benefits compared to cow and buffalo milk. However, nowadays, camel milk is being contaminated with cow milk, which poses a severe threat as it can alter the effectiveness profile of camel milk and cause serious problems in humans drinking it (Yao *et al,* 2023). Previously, adulteration in cow milk has been successfully detected using Fourier Transform Mid-Infrared Spectroscopy (FT-MIR). A study utilised FT-MIR and various AI techniques to detect adulteration in camel milk. Samples of camel milk were taken from China, Alxa League, and Inner Mongolia and were contaminated with varied concentrations of cow milk. The spectroscopy results were assessed using various AI models such as Principle Component Analysis (PCA), Linear Discriminant Analysis (LDA), Support Vector Machine (SVM), Artificial Neural network (ANN), etc. The results suggested that LDA model effectively discriminated between pure camel milk and adulterated camel milk, even in samples with minor cow milk adulteration. The quantitative model demonstrated excellent precision and accuracy within the range of 10–90 g/100 g of adulteration. Therefore, this supervised learning model can effectively be utilised in the early detection of adulteration in camel milk (Yao *et al,* 2023).

AI in drug discovery and diseases treatment in camels

The applications of AI have been focused much more on disease detection and health management so far. However, recent developments in AI-based tools and Machine Learning models have offered limited opportunities in treating camel diseases.

AI is useful in drug development. Yet, the applications in development of drugs specific for camel diseases are still not well developed. In this regard, treatment optimization and drug discovery are some of the major applications of AI. For instance, AI algorithms are useful in personalized medicine (Johnson *et al,* 2021). AI can help analyse health records, genetics, diagnostic results, and available treatment options to propose treatments for individual camels. Such approaches have proven useful in precision medicine in human health (Johnson *et al,* 2021; Rezayi *et al,* 2022).

AI has wide applicability in drug repurposing (Levin *et al,* 2020). Large-scale omics data, including genomics, transcriptomics, and proteomics data from camels, can be analysed by AI algorithms to find medications currently on the market and approved for other uses but may be modified to treat camel diseases. Chemists can then verify the therapeutic potential of these virtual compounds by having them synthesised and tested in the lab. AI models can predict the binding affinities of prospective drug candidates (Arabi, 2021) to target proteins implicated in camel diseases by analysing their molecular structures. While we tried to deliver new compounds for treating camel viral and parasitic diseases (Kandeel and Al-Taher, 2020a; Kandeel and Al-Taher, 2020b), the integration of AI in these efforts is expected to revolutionise the drug discovery for treating came diseases.

AI in camel-derived diagnostic and therapeutic products

The future of AI in camel biologicals, particularly focusing on developing of camel-derived antibodies and camel-derived nanobodies for diagnosis and treatment, represents a promising frontier in both veterinary and human medicine. Camels possess a unique immune system that produces antibodies significantly smaller than those of humans. These antibodies, known as nanobodies due to their miniature size, have garnered significant interest for their potential applications in various medical fields (Arbabi-Ghahroudi, 2022). The integration of AI into this research domain is set to revolutionise the ways in which these antibodies are discovered, optimised, and utilised.

Camel-derived antibodies have already shown considerable promise in diagnosing and treating a range of diseases. Their small size allows them to access and bind to targets in the human body that conventional antibodies cannot, making them excellent candidates for targeted therapy and imaging. For instance, nanobodies can penetrate deeper into tissues, offering superior diagnostic imaging capabilities and more effective delivery of therapeutic agents to disease sites, including tumors in cancer therapy (Al-Numair *et al,* 2022; Li *et al,* 2023). The application of AI in this field is twofold: first, in the discovery and development of new camel-derived antibodies, and second, in the optimisation of these antibodies for medical use. Machine Learning algorithms can analyse vast datasets of genetic information from camels to identify potential antibody candidates more rapidly than traditional methods. Furthermore, AI can predict the binding affinity of these antibodies to specific disease markers, accelerating the screening process for therapeutic candidates.

AI can help antibody development through different supervised and unsupervised learning approaches (Shaver *et al,* 2022). In the realm of predicting antibody models from molecular features, two main pathways exist. The first involves using an intermediary representation of antibody structure derived from molecular modeling, along with selected features. The second predicts directly from the amino acid sequence.

Recent advancements in AI have led to the development of various methods aimed at improving protein modeling especially in the field of camel derived nanobodies. Several AI-based tools were evaluated, including general protein modeling programs like AlphaFold2, OmegaFold, ESMFold, and Yang-Server, as well as those specifically designed for antibodies, such as IgFold and Nanonet, in their ability to model camel nanobodies (Valdes-Tresanco *et al,* 2023). The findings show that while these tools are effective at modeling certain parts of the nanobody, such as the framework and the first two complementarity-determining regions (CDRs), accurately modeling the third CDR remains a significant challenge (Valdes-Tresanco *et al,* 2023).

AI in camel management and welfare

A recent study addressed the challenge of classifying Arabian camel breeds—an essential task for breeding management, genetic improvement, conservation, and traceability—by leveraging advanced Machine Learning techniques (Alfarhood *et al,* 2023). The task is notably difficult due to the absence of standardized classification criteria, the high similarity between camel breeds, and limited data and resources. To overcome these obstacles, the authors propose a method utilising CNNs to classify images of six Arabian camel breeds: Waddeh, Majaheem, Homor, Sofor, Shaele, and Shageh. They compiled, preprocessed, and annotated a novel dataset of 1073 camel images for this purpose. The study tested various popular CNN architectures, including InceptionV3, NASNetLarge, PNASNet-5-Large, MobileNetV3-Large, and EfficientNetV2 (in small, medium, and large variants), to identify the most effective model for this application. The NASNetLarge architecture emerged as the most accurate, achieving a test accuracy of 85.80% on the dataset. Building on this success, the best-performing model, NASNetLarge, was integrated into a mobile application, aiming to facilitate its practical application in real-world scenarios for classifying Arabian camel breeds.

A study compared the effectiveness of seven Machine Learning methods in estimating the weight of dromedary camels from birth to 240 days of age, utilizing 458 records of body weight and 12 biometric measurements (Asadzadeh *et al,* 2021). The ML methods evaluated were Bayesian Regularised Neural Network (BRNN), Extreme Learning (EL), Random Forest (RF), Support Vector Machine with Linear (LSVM), Polynomial (PNLSVM), and Radial Basis Kernel (RNLSVM), and Linear Regression (LR). The models' performance was assessed using various statistical metrics through a 10 repeated 10-fold cross-validation process. The accuracy rates of the ML methods were: BRNN (94.93%), EL (93.22%), RF (94.61%), LSVM (93.2%), PNLSVM (95.43%), RNLSVM (94.93%), and LR (93.15%). The study concluded that while all methods were effective in predicting camel weight, PNLSVM was the most accurate, making it the recommended model for such estimations.

A study was conducted to predict the mature weight (MW) of male and female camels using morphological traits and hybrid Machine Learning algorithms. The study utilised biometrical measurements from eight Pakistani camel breeds, including birth weight, facial length, neck length, heart girth, body length, withers height, and hind leg length, to estimate MW. The researchers applied multivariate adaptive regression splines (MARS), random forest (RF), and support vector machine (SVM) algorithms for model development and used the artificial bee colony (ABC) algorithm to optimize these Machine Learning models for better accuracy. Evaluation of the models was based on mean absolute deviation, mean absolute percentage error, coefficient of determination, and root mean square error. The findings highlighted that the ABC-SVM model was the most accurate in predicting camel MW, demonstrating the method's effectiveness and its practical and research value (Iqbal *et al,* 2023).

Future perspectives

The future of AI in camel research is a fascinating area of exploration that promises to revolutionise the way we understand and manage these unique animals. Camels have been essential to human societies for thousands of years, providing transportation, milk and meat. However, their biological and ecological complexities have often been understudied compared to other livestock. AI, with its ability to process and analyse vast amounts of data, offers unprecedented opportunities for advancements in camel research.

One of the most promising areas of AI application in camel research is in health and disease management. Machine Learning algorithms can be trained on genetic, physiological, and environmental data to predict susceptibility to diseases, response to treatments, and optimal breeding strategies. This could lead to the development of more effective vaccines and healthcare strategies, reducing mortality and improving overall health.

In terms of breeding and genetics, AI can analyse genetic markers to identify traits associated with resilience, productivity, and adaptability to harsh environments. This could enhance selective breeding programs, helping to produce camels that are more resilient to climate change and capable of producing higher yields of milk and meat.

Nutritional research also stands to benefit from AI, as algorithms can optimise feeding strategies to improve growth rates and milk production while minimising waste and environmental impact. This could be particularly beneficial in arid regions where resources are scarce, and sustainable practices are essential.

Lastly, AI technologies such as robotics and autonomous systems could be employed for monitoring and managing camel herds in remote or harsh environments. Drones, for example, could be used for aerial surveys, providing real-time data on herd size, health and movement patterns.

Conclusion

This review underscores the transformative impact of AI on the health and welfare of camels, demonstrating significant advancements in diagnostic accuracy, disease prediction, and treatment optimization. AI's capabilities, from Machine Learning algorithms to Deep Learning techniques enhanced camel management practices, including weight estimation and milk adulteration detection. Despite these successes, challenges such as the need for comprehensive datasets and deeper applications in the fields of treatment of diseases. The review highlights the potential of AI to revolutionise the camel practice, offering promising avenues for improving camel health outcomes and welfare, and setting a precedent for the application of AI in camel healthcare.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data is available in the manuscript. Further details can be requested from the corresponding author.

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