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DIGITAL MONITORING TECHNOLOGIES IN VETERINARY ZOOLOGY: OPPORTUNITIES FOR DETECTING AND FORECASTING THE SPREAD OF PARASITES

Nurimova Periyzat Worazali qizi
Graduate of Samarkand State University of Veterinary Medicine, Livestock and Biotechnology
E-mail: nurimovaperiyzat573@gmail.com
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Abstract. The spread of parasites of veterinary importance is increasingly shaped by climate change, intensified animal movement and anthelmintic resistance, which challenges conventional surveillance based on sporadic laboratory examinations. This article reviews digital monitoring technologies applicable to veterinary zoology and evaluates their potential for detecting and forecasting parasite distribution. Four technology domains were analysed: automated and artificial intelligence (AI)-assisted diagnostics, geographic information systems (GIS) and remote sensing, mechanistic and machine-learning forecasting models, and precision livestock farming sensors. The results show that image-based automated egg counting achieves agreement with conventional methods sufficient for field decision-making, that satellite-derived temperature and vegetation indices reliably explain the spatial distribution of Fasciola hepatica and ixodid ticks, and that climate-driven simulation models can anticipate seasonal infection peaks. A four-layer integrated digital surveillance framework is proposed for Uzbekistan, and the main barriers – data scarcity, validation, connectivity and cost – are discussed.

Keywords: digital surveillance, veterinary parasitology, GIS, remote sensing, machine learning, automated faecal egg count, precision livestock farming, forecasting, One Health.

INTRODUCTION

Parasitic diseases remain one of the major constraints on livestock productivity and animal welfare worldwide. In Europe alone, gastrointestinal nematodes, liver fluke and lungworm in ruminants have been estimated to cost around €1.8 billion annually, most of it through production losses [1]. The epidemiology of these infections is dynamic: warming temperatures and altered rainfall patterns modify the development of free-living parasite stages and the activity of intermediate hosts and vectors, while anthelmintic resistance reduces the effectiveness of routine treatment.

Traditional parasitological surveillance relies on periodic collection of samples, microscopic examination in centralised laboratories and retrospective reporting. Such systems are slow, labour-intensive and spatially sparse, so they rarely allow timely intervention. Veterinary zoology – the study of animals, including parasites and vectors, in relation to animal health – is therefore undergoing a digital shift, in which data from automated diagnostic devices, satellites, weather stations and on-animal sensors are combined with computational models [2].

Despite rapid technological progress, evidence on these tools is scattered across disciplines, and their suitability for arid, resource-limited settings such as Central Asia has hardly been assessed. **The aim of this study** was to review and systematise digital monitoring technologies relevant to

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veterinary parasitology, to evaluate their capacity for detecting and forecasting parasite spread, and to propose an integrated framework adapted to the conditions of Uzbekistan.

MATERIALS AND METHODS

A structured narrative review was conducted. Scopus, Web of Science, PubMed and Google Scholar were searched for publications from 2010 to 2025 using combinations of the terms «veterinary parasitology», «livestock», «helminth», «tick», «GIS», «remote sensing», «machine learning», «deep learning», «automated egg count», «forecasting model», «precision livestock farming» and «sensor».

Studies were included if they (i) described a digital technology applied to parasites or vectors of domestic animals and (ii) reported performance data, validation results or a documented application for surveillance or forecasting. The technologies were classified into four domains: (1) automated and AI-assisted diagnostics; (2) spatial technologies (GIS and remote sensing); (3) forecasting models (mechanistic and statistical/machine learning); and (4) precision livestock farming (PLF) sensors. For each domain, the principle, data requirements, reported performance, level of field readiness and limitations were extracted and compared qualitatively.

RESULTS

1. Automated and AI-assisted diagnostics

Faecal egg counting remains the cornerstone of helminth diagnosis and of anthelmintic efficacy testing through the faecal egg count reduction test (FECRT) [3]. Several systems now digitise this step. Slusarewicz and co-authors combined fluorescent labelling of eggs with smartphone image capture and automated image analysis, obtaining counts comparable to the McMaster method [4]. For companion animals, the VETSCAN IMAGYST platform integrates a scanned faecal flotation slide with a deep-learning algorithm and demonstrated high agreement with expert parasitologists [5]. The main characteristics of these tools are summarised in Table 1.

Table 1. Digital technologies for parasite detection and forecasting: principles and field readiness

Technology	Principle / data source	Main application	Field readiness
Automated egg counting (fluorescence, smartphone imaging)	Image capture of flotation samples; computer vision algorithms	FEC, FECRT, targeted treatment decisions	High (commercial systems available) [4]
Deep-learning slide analysis	Convolutional neural networks trained on annotated parasite images	Species/genus identification of eggs and oocysts	Medium–high [5]
GIS and remote sensing	Satellite land surface temperature, NDVI, rainfall, land cover	Risk mapping of Fasciola, ticks, snail habitats	High for research; medium for routine use [6]
Mechanistic forecasting models	Degree-days, water balance, parasite life-history parameters	Seasonal risk forecasts, treatment timing	Medium [7]
Machine-learning models	Multisource data (climate, farm, laboratory, animal	Prediction of prevalence and	Low–medium [8]

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Technology	Principle / data source	Main application	Field readiness
	movement)	hotspots	
PLF sensors	Accelerometers, feeding and weight sensors, milk recording	Early detection of subclinical infection	Low–medium [9; 10]

2. Geographic information systems and remote sensing

GIS has been used in veterinary parasitology for two decades to integrate georeferenced prevalence data with environmental layers. Remote sensing supplies continuous, spatially explicit covariates such as land surface temperature (LST) and the normalised difference vegetation index (NDVI)[1]. In a pan-European analysis, Ducheyne and co-authors modelled the distribution of F. hepatica in dairy cattle using bulk-tank milk antibody results and environmental predictors [6]. These approaches convert sparse point observations into continuous risk surfaces that can guide targeted sampling and treatment.

3. Forecasting models

Mechanistic models translate weather data into parasite development using known biological thresholds. The classical approach accumulates growing degree-days above a base temperature. GLOWORM-FL simulates the free-living stages of gastrointestinal nematodes from daily temperature and rainfall [7]. Such models enable forecasts of the timing of pasture infectivity peaks and allow treatment to be scheduled according to actual rather than calendar risk. Statistical and machine-learning methods, including random forests and gradient boosting, are increasingly used where mechanistic knowledge is incomplete and large heterogeneous datasets are available, as already established in agricultural science more broadly [8]. Their predictive power, however, depends heavily on the volume and representativeness of training data.

4. Precision livestock farming sensors

Parasitic infection alters animal behaviour, often before clinical signs appear. In first-season grazing cattle, accelerometer data revealed changes in activity patterns associated with nematode parasitism [9]. PLF infrastructure – automatic weighing, milk recording and activity sensors – therefore offers an opportunity for continuous, non-invasive identification of animals requiring examination or targeted selective treatment [10]. At present these signals are non-specific and must be combined with parasitological confirmation.

5. Proposed integrated digital surveillance framework for Uzbekistan

Based on the reviewed evidence, a four-layer framework is proposed (Table 2). It builds on existing district veterinary services and the national hydrometeorological network, and prioritises low-cost technologies suited to smallholder-dominated livestock production.

Table 2. Four-layer framework for digital parasite surveillance adapted to Uzbekistan

Layer	Components	Expected output
1. Data acquisition	Smartphone-based egg counting in district laboratories; georeferenced	Standardised, georeferenced parasitological and environmental

[1]NDVI (Normalised Difference Vegetation Index) = (NIR − Red)/(NIR + Red), where NIR and Red are reflectances in the near-infrared and red bands; it serves as a proxy for vegetation cover and surface moisture, both relevant to the survival of free-living parasite stages and intermediate hosts.

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Layer	Components	Expected output
	sample records; tick collections; weather station and satellite data	data
2. Data integration	Central cloud database linked to veterinary information systems; common data standards	Unified national parasitology dataset
3. Analytics	Degree-day and water-balance models; GIS risk maps; machine-learning models after sufficient data accumulate	Seasonal and regional risk forecasts; hotspot maps
4. Dissemination and action	Web dashboard for veterinary authorities; SMS/messenger alerts for farmers; feedback of treatment outcomes	Timely, targeted prevention; resistance monitoring via FECRT

DISCUSSION

The review shows that digital technologies are at different stages of maturity. Automated diagnostics and GIS-based risk mapping are sufficiently validated for practical use, whereas machine-learning forecasting and PLF-based detection remain largely at research level.

The key value of digitalisation lies not in any single device but in integration. Point-of-care egg counts gain epidemiological meaning only when they are georeferenced and pooled; forecasting models become useful only when validated against field observations; and risk maps change practice only when they reach decision-makers in time. The proposed framework reflects this logic by linking data acquisition with analytics and feedback, following a One Health[2] orientation that also serves zoonotic threats such as tick-borne diseases.

The choice of technology should be guided by the decision it is intended to support. For individual-farm decisions, such as whether a group of lambs requires treatment or whether an anthelmintic is still effective, the priority is a rapid, reproducible egg count linked to the FECRT protocol [3; 4]. For regional decisions, such as when to issue a liver-fluke or tick warning, the priority shifts to spatially complete environmental data and validated risk models [6; 7]. Confusing these two levels leads either to expensive over-instrumentation of farms or to risk maps that are too coarse to change on-farm practice.

Validation deserves particular emphasis. For diagnostic devices, agreement with a reference method should be reported using appropriate statistics, such as Bland–Altman limits of agreement or Lin's concordance correlation coefficient, across the full range of egg counts encountered in the field [2; 4; 5]. For forecasting models, both discrimination (the ability to rank high- and low-risk areas or periods) and calibration (the agreement between predicted and observed infection levels) should be assessed on data not used for model building [7; 8]. For sensor-based detection, sensitivity and specificity must be estimated against parasitological diagnosis, since changes in activity or feeding may equally reflect heat stress, lameness or nutritional problems [9; 10]. Without such evidence, digital outputs risk creating a false sense of precision.

[2]One Health – a collaborative approach recognising the interdependence of human, animal and environmental health, promoted jointly by FAO, UNEP, WHO and WOAH.

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Economic considerations also shape adoption. Because the burden of helminth infections is dominated by subclinical production losses rather than by visible disease [1], the benefit of digital surveillance lies mainly in preventing losses that farmers do not see. Demonstrating this benefit through pilot projects with transparent cost–benefit analysis is likely to persuade farmers and policymakers more effectively than technological arguments alone.

Several barriers must be acknowledged. First, model transferability is limited: most validated models were developed in temperate Europe or Oceania, and their parameters require recalibration for arid continental climates, where moisture rather than temperature often limits free-living stages. Second, the lack of long-term, georeferenced baseline data restricts both validation of mechanistic models and training of machine-learning algorithms. Third, infrastructure constraints – rural internet coverage, device costs and staff training – affect adoption. Finally, data ownership and interoperability between veterinary, meteorological and agricultural information systems must be addressed through clear governance. A phased implementation, starting with pilot districts in irrigated valleys where parasitic risk is highest, is therefore recommended.

CONCLUSIONS

1. Digital monitoring technologies – automated and AI-assisted diagnostics, GIS and remote sensing, forecasting models and PLF sensors – substantially expand the capacity of veterinary zoology to detect and forecast the spread of parasites.

2. Automated faecal egg counting and satellite-based risk mapping are the most field-ready tools, while machine-learning forecasting and sensor-based early detection require further validation.

3. Climate-driven mechanistic models allow a transition from calendar-based to risk-based parasite control, supporting targeted treatment and slowing anthelmintic resistance.

4. For Uzbekistan, a phased four-layer digital surveillance framework integrating veterinary and hydrometeorological data is proposed; its implementation requires baseline data collection, local model calibration and investment in rural digital infrastructure.

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