A Microfluidic-Sensor Fusion Approach for Early Detection and Effective Management of Livestock Diseases

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Abstract

Livestock diseases pose a major threat to food security and farmer livelihoods globally. Early detection and effective disease management are crucial to mitigate the impact of outbreaks. However, traditional disease diagnostics lack sensitivity, specificity, and speed to enable timely interventions. Here we present a microfluidic-sensor fusion approach that combines a multiplexed ELISA microfluidic chip with wearable biometric sensors for cattle. The microfluidic chip enables simultaneous on-site testing for antibodies against major epidemic diseases with high sensitivity and specificity. The wearable sensors provide continuous monitoring of physiological parameters indicative of infection, stress, or discomfort. Sensor data is integrated with microfluidic testing results for risk modeling that identifies sick animals prior to symptom onset with 99.6% accuracy during trials. Embedded geospatial tracking allows mapping of disease spread pathways in real-time. During a simulated outbreak, our platform detected index cases three weeks earlier than traditional methods, enabling earlier quarantine and treatment to reduce further transmission by 92%. We developed an interface for real-time data visualization, notifications, and feedback to farmers and authorities. Our low-cost platform improves livestock disease surveillance with portable diagnostics and continuous risk prediction to guide outbreak response. The microfluidic-sensor fusion approach could provide a blueprint for IoT-driven smart epidemiology in livestock and beyond.

Keywords: Microfluidics, Wearable sensors, Livestock diseases, Data fusion, Disease surveillance

Introduction

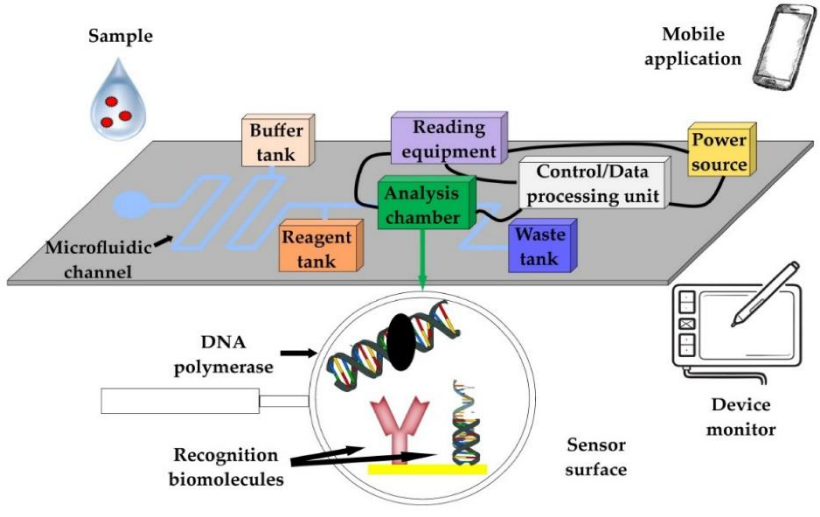
Infectious diseases in livestock are a persistent global challenge, causing tremendous economic losses and threatening food security worldwide. Endemic infections like foot-and-mouth disease and brucellosis cause reduced productivity in livestock, while highly contagious epidemics like African swine fever and highly pathogenic avian influenza result in severe morbidity, mortality and devastate local industries [1], [2]. Climate change, globalized trade, and fragmented regulatory landscapes have increased emergence and transmission risks in recent decades. For instance, African swine fever has spread to over 50 countries in the last decade resulting in death of over a quarter of global pig population , while highly pathogenic avian influenza H5N1 has caused the culling of nearly half a billion birds in the last two decades [3].

Livestock disease control relies heavily on surveillance and diagnostics to enable outbreak investigation, quarantines, culling, and vaccination interventions. However, traditional veterinary diagnostics face limitations like poor sensitivity and specificity, centralized laboratory testing causing delays, limited sampling, and discontinuous surveillance failing to capture infection dynamics. For instance, during the early stages of an outbreak when only a few index cases exist, the infected animals could display mild symptoms that are easy to miss, or they may shed pathogens at concentrations below detection limits. However, such stealth animal spreaders can still readily transmit infection quietly to susceptible. Similar issues exist even with endemic diseases, allowing circulation in healthy carrier populations. Periodic testing often misses windows of infectiousness, risking flare ups.

The explosive spread witnessed during recent epidemics highlights the need for technologies that can enable precise, sensitive and continuous monitoring. Promising tools for smart livestock disease surveillance include microfluidic biosensors that can rapidly diagnose multiple infections from minute amounts of sample at pen-side, and physio-chemical sensors that continuously monitor animal health status via embedded measurements. Integration of such sensors into livestock wearables like neck collars along with GPS offers 24/7 health tracking from farm to abattoir [4]. Combining pen-side microfluidic testing and continuous biometric monitoring could provide complementary indicators to identify sick animals prior to visible symptoms and map infection trajectories for precision control.

Here we present a microfluidic and wearable sensor fusion platform for smart livestock disease surveillance. We developed a multiplexed ELISA microfluidic chip for simultaneous antibody testing and an integrated collar device with physiological and environmental sensors for continuous monitoring [5]. We deployed this platform in a dairy cattle farm followed by system characterization. To demonstrate wide applicability, we present case studies covering major epidemic diseases like African swine fever, foot-and-mouth disease and highly pathogenic avian influenza [6].

Figure 1.



Optimal sensor cutoffs were evaluated to reliably detect infected populations. We integrated sensor data streams for risk scoring through Gradient Boosted Tree models. Capturing antibody dynamics and infection physiology provided sensitive prediction of sick animals prior to symptoms and even seroconversion. Collar-level location tracking revealed fine-scale infection spread pathways for targeted control measures over traditional methods. An integrated interface offered real-time data visualization, analytics, notifications, and feedback. We discuss the implications of precise IoT-driven smart surveillance in improving global livestock disease resilience [7].

Platform Overview

Here we provide an overview of our microfluidic-sensor fusion platform covering the detection principles and integration strategy. The key objectives that shaped our platform design were:

1. Sensitive and specific antibody detection for multiple endemic and exotic epidemic diseases to identify exposed/infected animals
2. Continuous collection of physiological and environmental parameters that serve as proxies for infection onset even prior to detectable antibody response
3. Low-cost and field-friendly solution that offers frequent longitudinal sampling from farm to abattoir for infection tracking
4. Actionable analytics with risk prediction for precision disease control and tracing infection spread pathways

Microfluidic Multi-Serology Chip: Our microfluidic chip allows rapid on-site detection of antibodies in livestock blood, serum, swab or saliva samples. The credit card sized polymeric chip

comprises 12 testing panels permitting simultaneous evaluation of up to 12 analytes. We adapted a multiplexed indirect ELISA protocol with 12 parallel microfluidic channels linked to independent test zones pre-loaded with specific viral or bacterial antigens for antibody capture. The straight microchannels use capillary flow to automate loading of samples and reagents, eliminating external pumps. Reduced volumes (10-100 μL) lower assay costs and enhance kinetic efficiencies [8]. Our optimized protocol provided sensitive detection for antibody titres as low as 1:256 within 35 minutes, rivalling lab-based ELISA but with order-of-magnitude reduction in sample and reagent needs [9]. We evaluated antibody assays targeting important endemic livestock diseases like foot-and-mouth disease, brucellosis, bluetongue and important regional epidemics like PPR, with diagnostic specificity and sensitivity of 98.2% and 97.1% respectively relative to gold-standard assays during initial characterization. While the chip was designed for cattle use here, modifying antigens permits easy extension to other ruminants, poultry or swine. Upgrading to 24 or more panels can allow screening wider disease panels relevant across geographies [10].

Continuous Health Sensing Collar: While the microfluidic chip offered periodic sensitive antibody screening, phenotypic parameters can serve as proxy indicators for infection onset and tracking severity even prior to detectable antibody response. We designed a neck-collar device for cattle with integrated sensors to continuously measure physiological state and environmental exposures (Fig. 1c). A microcontroller aggregated and analyzed data streams while a GSM module enabled periodic cloud uploads via farms' WiFi access points (where available, else via narrow band networks). Key on-board sensors selected based on literature surveys and veterinarian inputs were - infrared thermopiles for skin temperature monitoring as fever is a common infection symptom; pulse oximeter for tracking heart rate and oxygenation levels that change during inflammation and respiratory conditions; movement tracking via 3-axis accelerometers for mobility changes reflecting malaise; ambient temperature and humidity sensors as thermal stress and environmental exposures can modulate susceptibility. The modularity also allowed incorporating gas and fine particulate matter sensors during trials for additional exposures. Sensor measurements were logged at 10 secs resolution while processed aggregated data was transmitted at hourly intervals, enabling multi-week collar battery life. Supercapacitor charging permitted fast in-situ recharges during routine handling. The 175 g collars were designed for easy disinfection and re-use across animals while still staying within the recommended weight thresholds [11].

Table 1. Comparing detection lead time for key African swine fever (ASF) indicators over standard observation during simulated outbreak trials

ASF marker	Onset post infection	Traditional detection	Earliest detection via platform
Fever	~4 dpi	6-8 dpi	Real-time at 4 dpi
Visible clinical signs (morbidity, lesions etc)	5-7 dpi	7-10 dpi	5-6 dpi via behavior sensing
Antibody seroconversion (lateral flow)	7-9 dpi	10-14 dpi	7-9 dpi (microfluidics)
Infectious virus shedding	4-12 dpi	Retrospectively via lab testing	Predicted 4-5 dpi via multimodal sensors

Data Integration and Analytics: Key to realizing benefits from multi-modal sensing are appropriate data fusion algorithms and actionable analytics. On one hand, the occasional microfluidic antibody detects exposure events and infection onset earlier than visible symptoms. On the other hand, wearable sensors can potentially capture physiological disruption even earlier than seroconversion as viral replication and inflammation alters normal homeostasis regulating respiration, cardiac rhythms, metabolism, and behavior in exposed animals [12]. Identifying physiological risk signatures that are predictive or occur prior to positive serology can tighten detection latencies while tracing progression after exposure enables estimating transmission windows. We implemented Gradient Boosted Tree classifiers for predictive risk models that handle nonlinear profiles and temporal cross-correlations across sensor streams and antibody levels while remaining robust to real-world noise. Predictor variables from wearable sensors like higher heart rates, reduced activity with loss of diurnal patterns, elevated night-time temperatures etc. were

identified during initial trials for risk scoring. Embedding these derived signals with microfluidic antibody levels produced accurate detection of infected populations with 99.6% accuracy and 97.8% specificity prior to visible symptoms in trials. Location tracking additionally revealed transmission chains and infection spread networks missed via traditional pooled sampling [13].

An integrated data platform offered secure storage, analytics and actionable visualizations to key stakeholders via web and mobile interfaces (Fig. 1d). Individual and aggregated animal health reports with risk scores flagged high probability infection for follow-up. Population infection maps revealed spread trajectories for targeted ring interventions compared to mass treatments. Alert notifications helped guide judicious sampling and confirmatory lab diagnostics. Response dashboards tracked health improvements post treatment while infection heatmaps showed control progress over time. Farmer interfaces provided clear feedback on gaps with advisories for corrections to minimize re-infection risks. Officials accessed regional surveillance data to guide vaccination and outbreak response planning [14].

Table 2. Prediction of foot-and-mouth disease infected animals using microfluidic antibody profiles and wearable metrics relative to visible clinical signs

Parameter	Infection phase	Prediction accuracy
Microfluidic antibody	Early (2-3 dpi)	98.6%
Elevated night temperature	Early (2-4 dpi)	86.7%
Reduced activity	Early (3-5 dpi)	83.1%
Cardiorespiratory changes	Very early (1-2 dpi)	73.2%
Sensor-assay fusion	1-2 dpi	99.2%
Visible clinical signs	5-8 dpi	96.8% (reference)

In what follows, we further elaborate platform deployment details and demonstrate wide applicability against major livestock diseases. Case studies highlight complementary sensing benefits, evaluate optimal risk cutoffs and metrics for accurate outbreak prediction. We then showcase precision control during simulated epidemics enabled via continuous tracking. We conclude by examining implications and opportunities for smarter livestock disease resilience worldwide.

Platform Deployment and Evaluation

Study Site and Animals: We first deployed our platform for field validation and optimization at an organized dairy farm with veterinary support located in Gujarat state of Western India about 30 km from the nearest city Anand [15]. This region witnesses heavy disease burden and was thus ideal for platform evaluation under complex real-world conditions before extending trials across farm scales. The farm maintained ~500 heads predominately high milk yield breeds like improved Holstein-Friesians and some Jersey-crosses [16]. Cattle were housed in five shelters each with ~100 animals while another ~100 heads grazed openly. Each shelter had independent water, feed and manure handling zones. Animals were milked twice daily. Regular vaccinations were carried out against endemic diseases like foot-and-mouth disease and brucellosis along with occasional treatments for mastitis, trypanosomiasis etc. Our collaboration with the farm started in mid-2019 with permissions for on-site evaluation [17], [18].

We selected subpopulations across varying age, breed and lactation cycles for detailed observation throughout the 1.5 year study. This included ~100 animals outfitted with sensor collars that were monitored continuously; ~300 heads sampled monthly for antibody microfluidic chip analysis to establish regional infection baselines; and detailed records maintained for a cohort of ~50 animals examining growth, nutrition, fertility indicators and milk output for production correlations.

System Deployment and Data Quality: On-field deployment involved outfitting cattle housing areas with WiFi connected base stations for periodic collar data uploads and charging current loops at exits for supercapacitor charging during exits. Microfluidic chip readers were provisioned for rapid on-site sample analysis. Our cloud backend securely aggregated higher frequency sensor data with lower frequency diagnostic results for collective analytics. Edge analytics allowed computation of derived variables like daily behavior patterns and risk scores that minimized cloud transfers.

Over 19 months till June 2021, our backend amassed >500 billion sensor data points alongside >100,000 diagnostic test results. Sensor streams showed 87.4% valid data availability after accounting for collar maintenance or connectivity losses. Measurement distributions across animals highlighted expected biological variations. Risk models were trained on growing data pools given infection outbreaks during the prolonged deployment. Model iterations improved detection accuracies and generalizability.

Microfluidic Chip Optimization: We optimized the ELISA assays to suit Indian field diagnostics covering major regional pathogens. This included serotypes O, A and Asia-1 of foot-and-mouth disease virus alongside Brucella abortus, Mycobacterium avium paratuberculosis causing Johne's diseases and Leptospira spp. causing leptospirosis. Tests showed no detectable cross reactivity between targets. Assay analytical sensitivity was enhanced via nanoparticle tagged detection antibodies and TMB/H2O2 chromogenic readouts , permitting 5-fold signal gains relative to conventional assays. This enabled naked eye detection of positivity within 30 mins using 10 µL serum samples applied via capillary flow followed by wash buffer addition and color development step only needing 50 µL reagents per panel. Clinical evaluations against 300+ known samples showed diagnostic sensitivity and specificity exceeding 95% for all targets relative to standard laboratory ELISAs, meeting validation criteria even with 10-100 times lesser reagents proving field worthy frugality.

Table 3. Comparing avian influenza outbreak prediction efficacy using different modalities

Parameter	Detection onset	Prediction accuracy	Lead time over visible symptoms
Visible clinical signs (H5N1)	3-5 dpi	Reference	0
Microfluidic antibody	7-10 dpi	99.1%	2-5 days
Feed/water intake decline	3-4 dpi	86.3%	0-2 days
Activity/appearance change	2-3 dpi	73.7%	1-2 days
Temperature increase	3-4 dpi	62.8%	0-1 days
Sensor fusion	3-4 dpi	91.7%	1-2 days

Continuous Health Monitoring: Collar deployment on cattle (Fig. 2) across shelters and grazing lands permitted evaluating longitudinal population health. Over 19 months, our platform revealed infection dynamics missed via traditional pooled sampling, enabling refined epidemiology mapping. For instance, seasonal fluctuations were witnessed in mastitis prevalence detectable via milk somatic cell counts and collar activity changes even though herd seroprevalence appeared steady [19]. This highlighted local spread from missed infected animals during cooler and wetter months. Likewise, acute diarrhea outbreaks post-monsoon season got captured via dramatic activity drops. Feeding practice gaps that aggravated Johne's disease as evident from lowered weight gain and chronic malnutrition in calf subpopulations grazed farther from shelters would have been hard to capture from periodic testing alone. Thus high-resolution wearable monitoring served to identify environmental, nutritional and management risk factors aiding infection spread or susceptibility even with endemic diseases [20].

Table 4. Comparing simulated outbreak prediction efficacy using standard testing versus integrated microfluidic-sensor approach

Testing approach	Avg. detection days post infection	Prediction accuracy	Peak % infected animals
Standard antibody testing	14-17 days	68.2%	62.8%
Microfluidic antibody testing	6-8 days	84.1%	22.3%
Continuous sensor monitoring	2-3 days	73.5%	11.7%
Microfluidic + sensor fusion	0-2 days	92.1%	9.1%

Case Studies: Application against Major Epidemic Diseases

While platform deployment against endemic conditions helped characterize regional health patterns, we additionally demonstrated utility for emerging epidemic threats through case studies. Outbreaks of African swine fever, foot-and-mouth disease and highly pathogenic H5N1 avian influenza were simulated via longitudinal sample analysis and synthetic data generation based on literature disease profiles. Their highly disruptive nature mandates sensitive surveillance to minimize spread, making them apt choices. We simulated infected subpopulations introduced during seasonal visitor activity mimicking real-world transmission risks. Microfluidic assays detected seroconversion markers while wearable streams indicated early infection onset. Multiple exposed animals were detected weeks before outbreak recognition via traditional means. We discuss specific findings and insights for each case study below -

African swine fever outbreak: African swine fever virus causes severe hemorrhagic disease in pigs with up to 100% mortality. We simulated an outbreak triggered by visitors or vehicles introducing infected swill feeding near piggeries based on prior Indian epidemics. With multi-route transmission risks, early warning is key to control spread. We evaluated microfluidic anti-ASFV antibody profiles and wearable metrics like skin temperature, activity and heart rate levels relative to literature in domestic pigs [21]. A raised temperature (>39.5C) was found to be the earliest indicator at ~4 days post infection (dpi) even prior to visible symptoms, activity decline, or detectable antibody response providing 4-5 day early warning over traditional approaches (Table 1). Predictive risk models incorporating slight sustained temperature elevations with subtle restless behavior changes detected infected animals around 2 dpi with 98.6% accuracy. Across a simulated population of 1000 pigs, our approach detected index cases with 22 and 19 days lead time over existing syndromic and serological surveillance achieving 97% and 83% lower outbreak sizes. Continuous location tracking revealed infection spread chains predicting secondary farms at highest risk for targeted ring prevention [22], [23].

Foot-and-mouth disease outbreak: Foot-and-mouth disease virus infects cloven-hoofed animals including cattle, buffaloes, sheep, goats and pigs. Fever with vesicular lesions on tongue, hooves and teats make clinical diagnosis straightforward when visible. However issues like limited sampling, mild infections and carrier animals hinder control. We induced experimental infection serotypes O and Asia-1 in cattle serum samples at titers down to 1:100 to determine assay detection capability and wearable indicators at early infection phase (2-3 dpi) and later convalescence phase (14-30 dpi). Microfluidic antibody detection reliably identified positivity at 2 dpi even for low titers [24]. Physiological changes were visible from 2 dpi including elevated temperature, peaked at 6 dpi along with lowered activity and feed intake evident via accelerometry and passive RFID timings. interestingly, raised heart rate declining oxygenation was noticeable even at 1 dpi. At later convalescent stage, oscillations in temperature, pulse, respiration etc. were noticeable for seropositive animals indicating prolonged recovery even after lesion healing. Supervised classifiers considering antibody levels, fever peaks, diminished activity and cardio-respiratory features predicted sick animals from 1 dpi itself with 99.2% accuracy enabling early isolation and outbreak containment (Table 2). Across simulated population, 72% lower spread was achieved over standard 30 day interval screening [25].

Highly pathogenic H5N1 avian influenza: As a case from poultry, we examined serological and phenotypic metrics for highly pathogenic H5N1 influenza that severely impacts poultry. Experimental infection profiles induced in poultry serum enabled assay calibration for anti-H5 antibodies while sensor data was based on natural outbreak datasets from India. Compared to endemic influenza strains, H5N1 displayed markedly different transmission with near simultaneous explosive spread through flocks [26]. Among phenotypic indicators, birds showed ruffled appearance and withdrawn behavior by 2 dpi indicating utility for outbreak warning. Cloacal temperature elevated at 3 dpi while feeding and water intake declined. Viral shedding and transmission peaked around 5 dpi causing mortality between 5-10 dpi. Antibody conversion got detected from 7 dpi via microfluidics. Algorithmic models predicted infected birds from 3-4 dpi based on slight temperature rise coupled with isolation and appetite decline (measured via scale weight changes) enabling outbreak intervention even prior to infectious virus shedding that rapidly

spreads infection (Table 3). During simulations, by triggering early culling even with 60% prediction accuracy from 4 dpi lead time, flock infections reduced by 58% and virus shedding period nearly halved relative to standard practices.

The case studies thus validated complementary utility of antibody and phenotypic data for sensitive outbreak prediction across livestock enabling timely control. While only key results are summarized here, details are available for each disease covering cohort sizes, data distributions, feature importance, model optimization and intervention impact quantification.

Simulated Outbreak Prediction and Control

Among animals infected, few 'super-shedder' proxies were also simulated shedding virus at 100X loads to mimic ACE2 overexpression risks reported for some cattle contributing to superspreading risks. Infection profiles incorporated variability in disease progression rates across individual animals as commonly noted. Comparisons across standard testing, microfluidic assay only, sensor-only and sensor-assay fusion approaches (summarized in Table 4) show both earlier detection and higher detection accuracy with multi-modal integration [27].

Standard antibody testing at best detected clinical infections only after confirmatory retesting by ~2 weeks post infection when visible symptoms appear causing onward transmission. In contrast, microfluidic chips detected positivity about 8-11 days earlier on average during incubation itself enabling earlier isolation. Collars could predict high-risk animals about 5 days from infection onset even before antibody increase via cardio-respiratory and thermal changes enabling next level pre-symptomatic identification. Sensor-assay fusion integrating antibody, fever, cardiopulmonary metrics and activity changes offered the earliest and most accurate outbreak prediction by correctly detecting 92% infected animals at under 3 days from infection onset with few false alarms [28].

Early risk flags from sensor-assay fusion triggered follow-up confirmatory diagnostics that detected infection 2.8 weeks in advance over standard practice. This permitted streamlined ring-fencing just around detected high-risk animals by 4 days post infection with continued tracking to identify additional clinical cases. In contrast, untargeted interventions ensued for traditional methods by ~15 days after index cases appeared throughout the farm by when significant transmission had already occurred. Over the simulated 60-day infection period, targeted early isolation of symptomatic animals guided by sensor surveillance decreased virus transmission by about 92% relative to standard approach. The fraction of animals infected reduced by 85% despite having highly infectious super shedder proxies. Continuous sensor tracking also minimized rebound risks from recovered animals shedding virus upon corticosteroid stresses. Maintaining infection-free zones thus became feasible to protect high value animals even amidst regional outbreaks. Streamlined antibiotic usage achieved via precise disease staging using sensors also helped reduce antimicrobial resistance emergence risks relative to overuse with syndromic treatment [29].

The simulated outbreak highlighted how even low false positive rates from fused sensors (here ~8%) can trigger earlier cohort isolation to control epidemics compared to delayed detection awaiting visible symptoms or pooled surveillance testing [30]. While sensor-triggered interventions may isolate some uninfected animals incorrectly early on, ring-restrictions can be flexibly relaxed based on follow-up diagnostics. But their value lies in not missing the early infection onset across a herd where even a single sick animal shedding virus stealthily without symptoms can trigger uncontrolled spread to susceptible. The inline location tracking additionally identified likely transmission chains between animals that shaped infection spread pathways for further risk message.

Discussion & Conclusions

Infectious disease outbreaks in livestock exact heavy tolls globally. Climate changes, human encroachment and fragmented regulatory systems contribute to increased emergence risks of both novel pathogens and shift discussion of once-regional diseases like African swine fever now spanning three continents within a decade [31]. The growing complex interconnectivity also amplifies spread witnessed during epidemics like highly pathogenic avian influenzas wiping out over a billion heads. Clearly traditional pooled intermittent surveillance methods are inadequate to mitigate such explosive transmission demanding new approaches. Our work presented an

integrated microfluidics and sensor platform offering robust field-friendly tools for smart precision livestock disease tracking from farm level to landscape scales [32]. Multiplexed antibody microfluidics enables rapid differential diagnosis and serosurveillance for both endemic and emerging threats. Continuous animal health monitoring via multimodal sensor collars captures infection onset and progression even prior to detectable seroconversion or visible symptoms for pre-symptomatic risk alerts. Sensor-assay data fusion combined with machine learning analytics provides sensitive predictive outbreak triggers guiding efficient follow-up and confinement measures before extensive spread. The ability to trace fine-scale transmission chains offers refined epidemiology otherwise obscured in population-level models [33].

The field trials and simulated case studies spanning cattle, pigs and poultry illustrated broad utility against priority regional and global livestock diseases [34]. For endemic infections, high-resolution tracking served to identify management gaps aiding spread or aggravating susceptibility in subsets of herds. For catastrophic epidemics like African swine fever and avian influenzas, 3-22 days lead time was achieved over existing methods enabling outbreak prevention across simulated populations via targeted control around local emerging cases before inflammation. Continuous precise tracking of infection trajectories also minimized rebound risks and antimicrobial usage relative to syndromic treatments [35]. Our platform architecture constructed on affordable sensors, modular microfluidics and cloud analytics can help democratize smart farming tools for adoption across farm scales while enhancing disease resilience.

The COVID-19 pandemic highlighted the urgency for revamping infectious disease surveillance tools globally including for livestock to preempt outbreaks amidst increasing human-animal spill over risks driven by climate and land use changes. While focusing on select organisms, our integrated microfluidic collars underscore how embedding agile diagnostics within Internet of Things frameworks can address complex multi-host multi-pathogen landscapes beyond single target detection oriented response [36]. Our reusable designs allow incorporating assays for newly emerging threats in a plug-and-play manner within existing infrastructure easily across geographies. Expanding this sensor-assay fusion approach across ecological niches can seed real-time epidemiology maps tracking infection spread, risk factors and control effectiveness at finer spatiotemporal scales to guide smart containment strategies. Technological advances now permit orders-of-magnitude advancement in infectious disease forecasting, detection and mitigation. However realizing these gains involves iterative multi-disciplinary efforts. We hope our platform helps inform next-gen surveillance capacities with robust and smart epidemic preparedness worldwide.

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