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Syndromic surveillance in slaughterhouses: A scoping review

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ABSTRACT

Syndromic surveillance in slaughterhouses represents a valuable approach for early disease detection and large-scale animal health monitoring. Despite its increasing application, the evidence base remains fragmented, and important methodological and terminological inconsistencies persist. This scoping review seeks to provide an integrated overview of existing systems, highlight cross-cutting patterns and limitations, identify knowledge gaps, and inform future standardization and optimization efforts in this field. Following the PRISMA-ScR guidelines, we reviewed peer-reviewed studies reporting the use of slaughterhouse-derived data for syndromic surveillance. Searches were performed in four electronic databases and major conference proceedings; proceedings were eligible for inclusion only when they had been published in indexed, peer-reviewed journals. Thirty-four studies published between 1987 and 2024 were included. Research activity has increased markedly over time but remains geographically concentrated in Europe (n = 11) and the Americas (n = 16), with pigs and cattle being the most frequently studied species. Across studies, substantial heterogeneity was observed in terms of syndromic classifications, analytical methods, and system design. Slaughterhouse-based syndromic surveillance is most commonly used for early disease detection, monitoring of animal health and welfare, and supporting epidemiological investigations. The reported strengths included broad population coverage, cost-effectiveness, and feasibility within existing inspection systems. However, recurring limitations were related to data quality, reporting biases, limited validation, and poor standardization across systems. Overall, syndromic surveillance in slaughterhouses shows considerable potential as a complementary component of animal health surveillance, particularly for early warning and population-level monitoring. Advancing its effective implementation will require greater methodological harmonization, improved validation, and stronger integration with other surveillance data streams within national and international One Health frameworks.

1. Introduction

According to the Pan American Health Organization (PAHO, 2017), surveillance systems play a central role in monitoring changes in population health and supporting timely public health decision-making. Surveillance is defined as the systematic and continuous monitoring of the frequency, distribution, and determinants of health events and their trends in the population across time, space, and individual characteristics (Porta, 2014). It serves to monitor priority health events and public health interventions, test hypotheses, and support evidence-based decision-making in health policy. The surveillance cycle consists of four stages following the identification of the event of interest: (i) data collection, (ii) data analysis, (iii) data interpretation, and (iv) information dissemination to relevant authorities. The core purpose of these stages is to organize and guide the response actions of the health system at different levels, facilitating the prevention and control of identified health problems and thereby reinforcing its overall impact (PAHO, 2017). In this context, the effectiveness of surveillance systems

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increasingly depends on their ability to generate timely, integrated, and actionable information from diverse data sources, particularly for early detection and situational awareness.

One form of surveillance is syndromic surveillance (SyS), which is defined as the use of prediagnostic health data (i.e., syndromes) collected in real time—or in near real time—from various sources, such as absenteeism reports, laboratory results, clinical consultations, internet searches, pharmacy sales, poison control center records, and emergency medical service data. By analyzing this information across spatial and temporal dimensions, SyS establishes alert thresholds and supports the characterization and monitoring of specific health risks. In doing so, it enhances the quality and timeliness of the public health response by reducing the time between the initial clinical presentation and the issuance of an epidemiological alert (Herrera et al., 2006). Unlike traditional surveillance systems that focus on specific diagnoses, SyS repurposes existing data—without altering original data collection protocols—to detect syndromes. This flexibility facilitates the early detection of both known and emerging diseases. For these reasons, PAHO (2017) advocates SyS as a strategic methodology to strengthen the performance of surveillance systems. These characteristics have stimulated growing interest in the application of syndromic surveillance beyond human public health, including in the field of animal health.

Public health syndromic surveillance is based on the premise that significant changes in population health manifest through detectable behavioral or utilization patterns (Vial and Berezowski, 2014). Similarly, in animal health syndromic surveillance, shifts in population health or welfare may be reflected not only through animal-level indicators but also through changes observed in human caregivers or other relevant actors (Vial and Berezowski, 2014). Accordingly, in AHSyS, a “syndrome” may encompass a wide range of indicators derived from animals, caregivers, or associated systems, provided that they reflect meaningful alterations in animal health or welfare conditions.

Efforts to develop SyS models for animal health have been documented since 2003. These initiatives were cataloged and assessed by the Triple-S Project (Syndromic Surveillance System) (Dupuy et al., 2013a; Hulth, 2014), which also provided a practical framework for their design and implementation (Vial et al., 2015). Animal health syndromic surveillance (AHSyS) models leverage diverse data sources, including laboratory reports, mandatory notifications, veterinary clinical records, farm production and mortality data, emergency veterinary services, web-based platforms, and slaughterhouse inspection records (Dórea et al., 2011). Among these, slaughterhouses stand out as a particularly valuable and strategic source of health information (Dórea et al., 2011; Weber, 2011; Dórea and Vial, 2016) owing to the mandatory ante-mortem and post-mortem veterinary inspections that generate high-quality health data (FAO/WHO, 2024). However, despite their recognized potential, the integration, standardization, and comparative evaluation of slaughterhouse-derived data within AHSyS remain limited, fragmented, and insufficiently synthesized at the global level.

Given the fragmented, heterogeneous, and methodologically diverse nature of the literature on slaughterhouse-based animal health syndromic surveillance, a ScR is considered the most appropriate approach to systematically map existing evidence, identify cross-cutting patterns, and highlight key knowledge gaps (Arksey and O'Malley, 2005; Pham et al., 2014). Like systematic reviews, ScRs follow a structured and replicable methodology to identify and characterize available evidence (Colquhoun et al., 2014; Pham et al., 2014; Young et al., 2014). Another key contribution of ScRs is their ability to highlight evidence gaps, thereby informing future research priorities and resource allocation. This approach is particularly appropriate in fields characterized by conceptual diversity, methodological heterogeneity, and uneven evidence distribution, such as slaughterhouse-based AHSyS.

Considering the fragmented and nonstandardized global information on this topic, we aimed to systematically identify and synthesize the literature on AHSyS in livestock slaughterhouses worldwide. Specifically, this ScR seeks to provide an integrated overview of existing systems, highlight cross-cutting patterns and limitations, identify knowledge gaps, and inform future standardization and optimization efforts in this field.

2. Materials and methods

2.1. Review protocol and team expertise

A ScR was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018). The research question, search strategy, eligibility criteria, and protocols for relevance screening, baseline characterization, methodological appraisal, and data extraction from relevant primary studies were developed and applied via a predefined and pretested protocol. This approach relies on predefined screening criteria, structured data extraction tools, and a sequential review process, allowing all steps of study selection and characterization to be clearly documented and applied consistently across the included studies. The review team included experts with multidisciplinary backgrounds in epidemiology, veterinary public health, and knowledge synthesis and information science.

2.2. Review question and search strategy

This ScR was conducted to address the following research question: What is the current state of evidence on SyS in livestock slaughterhouses worldwide? The initial search was performed on September 20, 2024.

Four electronic databases—OVID/MEDLINE, PubMed, SciELO, and Redalyc—were systematically searched. The search strategy involved three main components: the type of data analysis (SyS or other types of cluster detection), the target population (domestic livestock), and the data source (slaughterhouse inspection data). The following terms were used to identify relevant studies: (“syndromic surveillance” OR “early warning” OR “outbreak detection” OR “aberration detection” OR “anomaly detection” OR “early detection” OR “cluster detection”) AND (livestock OR cattle OR pig* OR horse* OR sheep OR goat* OR poultry OR fish OR stock OR cow* OR beef OR bovine* OR avian OR broiler* OR caprine* OR ovine* OR equid* OR equine* OR porcine* OR swine) AND (slaughterhouse OR “meat inspection” OR condemnation OR abattoir OR rejected OR “meat processing plant” OR “animal processing facility” OR “meat plant” OR “slaughtering facility”).

Proceedings from the Annual Meetings of the Society for Veterinary Epidemiology and Preventive Medicine (SVEPM), held between 2009 and 2024, the International Conferences on Animal Health Surveillance (ICAHS), held in 2011 and 2024, the International Symposia on Veterinary Epidemiology and Economics (ISVEE), held in 2012 and 2015, and the Annual Meetings of the International Society for Disease Surveillance (ISDS), held between 2011 and 2024, were manually screened to identify additional primary studies. Furthermore, the reference lists of six key review articles were also manually screened (Dórea et al., 2011; Gates et al., 2015; Huneau-Salaün et al., 2015; Muellner et al., 2015; Dórea and Vial, 2016; Vidal et al., 2016). Finally, two reviewers conducted a manual backward reference search (snowballing) from the studies included after full-text screening to identify any additional relevant sources.

2.3. Relevance screening and inclusion criteria

The citation selection process began with two reviewers independently screening the titles to identify potentially relevant records to the research topic. The same reviewers subsequently evaluated the 120 abstracts of the selected studies, applying predefined inclusion and exclusion criteria. This was followed by a comprehensive full-text review to confirm the relevance of each study in addressing the research question. Agreement between reviewers was assessed at each stage of the selection process via Cohen's kappa coefficient to quantify interrater reliability, with values ≥ 0.60 considered indicative of acceptable agreement. Any discrepancies were subsequently resolved through consensus among the authors. A detailed evaluation of the materials, methods, and results sections of each full-text article was performed, and any discrepancies were resolved through consensus among the authors. The inclusion criteria were limited to original research articles published in peer-reviewed journals in English, Portuguese, French, or Spanish. No restrictions were applied regarding the year of publication. The gray literature sources and the snowballing procedure are described in Section 2.2.

2.4. Study characterization and data extraction and analysis

Full-text articles from potentially relevant citations were assessed via structured tools developed *a priori* to guide relevance screening, data extraction, and study characterization. This evaluation relied on two sequential instruments created specifically for this review.

The assessment process involved two main instruments. First, a relevance screening tool based on three predefined questions (Supplementary Material 1) was applied to determine whether each article (i) addressed animal health syndromic surveillance, (ii) used slaughterhouse-derived data as a primary information source, and (iii) reported an implemented or operational surveillance system. Second, a comprehensive article-level characterization and quality-appraisal form (Supplementary Material 2) was used to systematically extract methodological and system-related information, including study objectives, species, data sources, analytical approaches, reported strengths and limitations, and system applications. Together, these tools ensured a transparent, standardized, and reproducible assessment of all full-text articles included in the review.

Data from eligible studies were independently extracted by two reviewers via a standardized data abstraction form. Discrepancies were resolved through discussion, with adjudication by a third reviewer when necessary. The analysis units considered were individual animals, farms, batches, and slaughterhouses. The extracted information was organized in Microsoft Excel spreadsheets (Microsoft Corporation, Redmond, WA) and analyzed descriptively via frequencies and percentages to support categorization, charting, and interpretation of the results and discussion. To further interpret the findings of this review, strengths, weaknesses, opportunities, and threats (SWOT) analysis was conducted to synthesize the key aspects influencing the design, implementation, and sustainability of slaughterhouse-based AHSyS.

3. Results

The electronic search, which combined the results from all the search platforms and excluded duplicates, yielded 161 citations potentially relevant to the scope of this ScR. These citations were published between 1968 and 2024. After title screening, 135 citations were deemed unrelated by consensus between two independent reviewers. A total of 26 citations were retained at the title screening stage (i.e., included by at least one reviewer). Nine additional articles were identified through snowballing, and four additional studies were identified from the proceedings of the International Conferences on Animal Health Surveillance (ICAHS), held in 2011 and 2024, resulting in a total of 13 additional articles.

In total, 34 articles met the inclusion criteria and were incorporated into the qualitative synthesis. The complete dataset detailing the systematic process of citation identification and selection is provided in Supplementary Material 2. Fig. 1 presents the ScR protocol and outlines the flow of study selection.

The first relevant article was published in 1987, and the most recent article was published in 2024. The 34 articles were distributed across 15 scientific journals; detailed publication counts per journal are provided in Table 1. All included articles were written in English. The temporal and geographical distributions of the studies included in this ScR were analyzed on the basis of the continent and country where the research

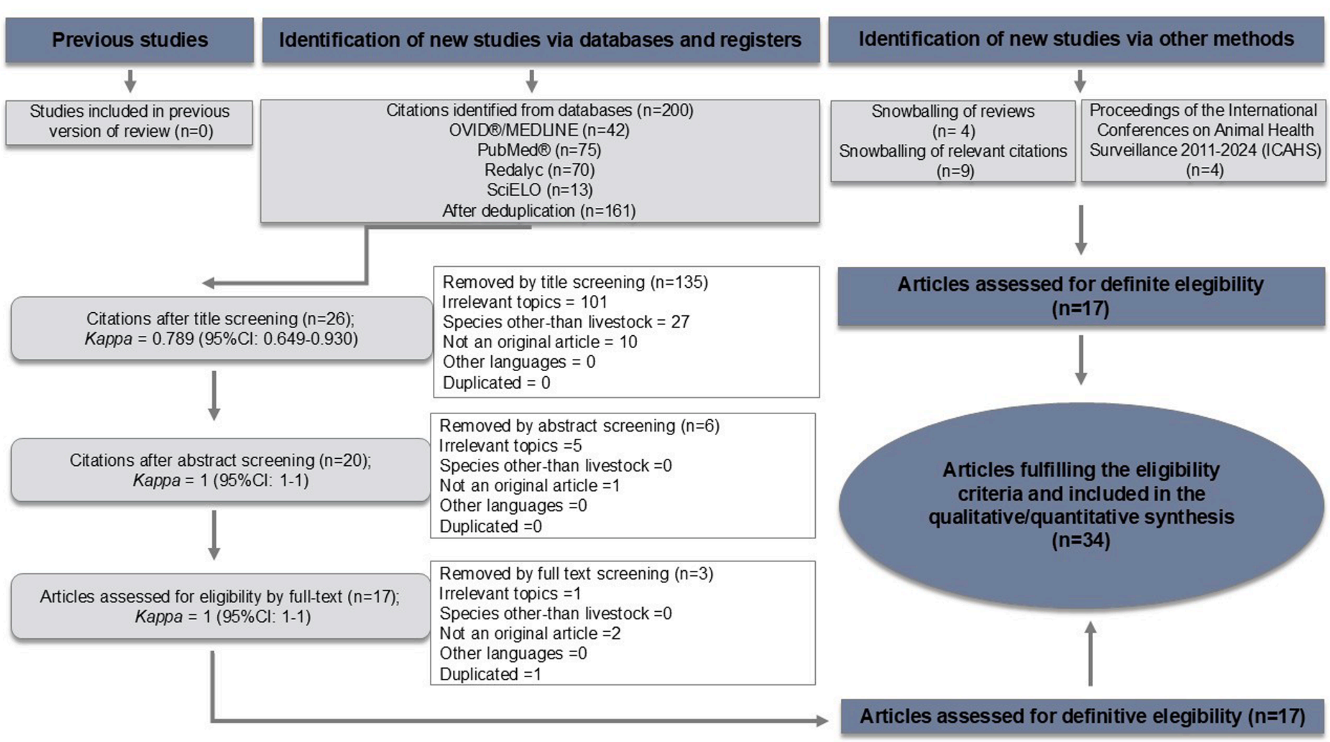

Fig. 1. Preferred Reporting Items for Systemic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018), describing the progress of the citations through the scoping review.

Table 1
Temporal and geographical distributions of the 34 relevant articles included in the scoping review on animal health syndromic surveillance (AHSyS) in slaughterhouses worldwide (1987–2024).

Continent/country	Total number of articles published in each 5-year period						Total
	1986–1990	2001–2005	2006–2010	2011–2015	2016–2020	2021-Present	
America	1	1	1	6	2	1	**12**
Canada	1		1	6			8
Colombia						1	1
United States		1			2		3
Asia						1	1
Japan						1	1
Australasia/Oceania				2			**2**
Australia				1			1
New Zealand				1			1
Europe		1		9	5	3	18
Denmark		1					1
France				3			3
Germany					1		1
Italy					1		1
Poland						1	1
Switzerland				4			4
United Kingdom				2	3	1	6
Various						1	1
No reported				1			**1**
Total	**1**	**2**	**1**	**18**	**7**	**5**	**34**

was conducted, as well as the 5-year period during which the articles were published.

Publication activity peaked during the 2011–2015 period (n = 18), accounting for more than half of all included studies, followed by a decline in subsequent intervals (2016–2020: n = 7; 2021–present: n = 5). This distribution may reflect a consolidation phase in the field rather than a continuous growth trend. Table 1 shows detailed country-level distributions and publication counts. Geographically, research output remains unevenly distributed, with a concentration of studies in high-income countries, whereas low- and middle-income regions are underrepresented despite often facing greater burdens of animal health threats.

Most studies rely on routinely collected surveillance data derived from national or regional animal health information systems, complemented in some cases by laboratory databases and field-level reporting tools. While several databases have been recurrently used, considerable heterogeneity has been observed in terms of data structure, accessibility, and integration across systems. A detailed overview of the databases and data sources reported across studies is presented in Supplementary Table S1.

Of the 34 articles reviewed, 19 were explicitly focused on AHSyS, whereas the remaining 15 addressed topics aligned with AHSyS principles without acknowledging or identifying them as such. Since AHSyS studies rely on data already available at the slaughterhouse, they typically do not include formal studies or sampling designs. Among the 15 non-AHSyS-focused articles, only three described the type or design of the study in their materials and methods section: two (Peterson et al., 2017; Guardone et al., 2020) reported an observational design, and one (Shadbolt et al., 1987) reported a survey-based approach. With respect to the operational status of the systems, six studies (Sánchez-Vázquez et al., 2011; Dupuy et al., 2013c; Eze et al., 2015; Correia-Gomes et al., 2017; Nienhaus et al., 2017; Alban et al., 2022), five focused on pigs and one focused on cattle, reported that the systems were active at the time of the study. Two studies (Amezcua et al., 2011; Pineda et al., 2022) indicated that the systems were inactive, and 26 articles did not specify the operational status of the surveillance system.

Among the 19 articles specifically focused on AHSyS, four did not explicitly align with the definition of SyS (Sánchez-Vázquez et al., 2011; Alton et al., 2012; Correia-Gomes et al., 2017; Haredasht et al., 2018). The primary aim of SyS is to monitor disease or well-being trends within defined populations and to identify cases or outbreaks with sufficient probability. Compared with traditional surveillance systems based on confirmed diagnoses, SyS enables faster detection and investigation of potential threats (such as morbidity, mortality, or major economic losses) affecting human or veterinary public health. This facilitates the planning, implementation, and evaluation of risk mitigation actions, enabling a timely and justified early response to emerging risks.

Based on the extracted data, syndromic surveillance systems ranged from relatively specific approaches —using narrowly defined indicators closely linked to conditions — to more nonspecific approaches relying on broad syndromic or prediagnostic indicators (e.g., general clinical signs or condemnation categories) intended to capture early, unspecific changes in animal health. These data can be medical (e.g., groupings of clinical signs, symptoms, injuries, partial or total carcass condemnations following meat inspection, or mortality data) or nonmedical (e.g., management indicators recorded at the slaughterhouse level, such as ante-mortem rejections or transport losses). Consequently, categorical variables are the most frequently used types of syndromic data in SyS applications, whereas continuous variables are relatively less common.

It was not possible to determine the total number of animals evaluated for each species, as the same database, covering the same period, may have been used in multiple articles. Consequently, reporting a cumulative number would not reflect a true count and would likely result in an overestimation. The objectives of AHSyS studies were predominantly oriented toward early outbreak detection, trend monitoring, and situational awareness, with fewer studies explicitly addressing system evaluation or decision-support outcomes. Analytical units vary substantially, ranging from individual animals to herds, regions, or national-level aggregates, reflecting differences in system design and data availability. Detailed classifications of the analytical units and study objectives are provided in Supplementary Tables S2 and S3, respectively.

Since AHSyS systems generate indicators to monitor specific syndromes in slaughtered animal populations, the choice and construction of each indicator depend on the type and structure of the variables available in the databases. These indicators may be expressed as percentages, proportions (e.g., prevalence), or other formats. Consequently, the application of AHSys varies according to the syndrome under surveillance, as different health conditions require distinct data inputs, indicator definitions, and interpretation approaches. Table 2 presents the potential applications of AHSyS on the basis of slaughterhouse data.

Across studies, AHSyS incorporates a wide array of syndromic categories and variables, encompassing clinical signs, production indicators, and mortality-related metrics. However, variable selection is often

Table 2
Reported uses of animal health syndromic surveillance (AHSyS) in slaughterhouses worldwide, including its role in establishing health monitoring indicators and contextual considerations, according to the 34 relevant articles included in the scoping review (1987–2024).

Monitoring objective	Considerations	Reference(s)
Diseases in general	Zoonotic, relevant, epidemics, coinfections	Shadbolt et al. (1987); Enøe et al. (2003); Salman et al. (2003); Alton et al. (2010); (2012); Amezcua et al. (2011); Hernández-Jover et al. (2011); Sánchez-Vázquez et al. (2011); Thomas-Bachli et al. (2012); (2014); Dupuy et al. (2013a); (2013b); (2013c); (2014); (2015); Neumann et al. (2014); Vial and Berezowski (2014); Eze et al. (2015); Muellner et al. (2015); Vial et al. (2015); Vial and Reist (2015); Correia-Gomes et al. (2016); (2017); Nienhaus et al. (2017); Peterson et al. (2017); Guardone et al. (2020); Lee et al. (2020); Buzdugan et al. (2021); Alban et al. (2022); Majewski et al. (2022); Narita et al. (2024)
Specific endemic diseases	Syndrome-based causes such as fasciolosis, fatty liver syndrome	Alton et al. (2013); Dupuy et al. (2013a); (2013b); (2013c); (2015); Vial and Reist (2014); Neumann et al. (2014); Vial and Berezowski (2014); Eze et al. (2015); Correia-Gomes et al. (2016); Buzdugan et al. (2021)
Nonspecific endemic diseases	System-based syndromes such as respiratory, renal, neurological, reproductive diseases, and emaciation	Dupuy et al. (2013a); (2013b); (2013c); Haredasht et al. (2018)
Nonendemic diseases	Rare or low-prevalence conditions such as erysipelas and bovine cysticercosis	Vial and Berezowski (2014)
Emerging diseases	Predicting the occurrence of new diseases.	Alton et al. (2010); (2013); (2015); Sánchez-Vázquez et al. (2011); Dupuy et al. (2013a); (2013b); (2013c); (2014); (2015); Neumann et al. (2014); Vial and Berezowski (2014); Eze et al. (2015); Correia-Gomes et al. (2016); Peterson et al. (2017); Haredasht et al. (2018); Buzdugan et al. (2021)
Notifiable diseases	Foot-and-mouth disease, CSF (classical swine fever), brucellosis, TB (tuberculosis), BSE (bovine spongiform encephalopathy), EIA (equine infectious anemia), HPAI (highly pathogenic avian influenza), rabies	Salman et al. (2003); Dupuy et al. (2014); (2015); Pineda et al. (2022)
Foodborne diseases	Based on sampling plan results supporting the HACCP system, including *Salmonella*, *E. coli* O157, *Campylobacter*, *Toxoplasmosis*, mycotoxins, and *Trichinella*	Dupuy et al. (2015); Muellner et al. (2015); Alban et al. (2022)
Disease freedom	Providing evidence of disease absence for international trade (SPS) and supporting the designation of pathogen-free herds or zones	Salman et al. (2003)

Table 2 (*continued*)

Monitoring objective	Considerations	Reference(s)
Use of veterinary drugs	based on the results of meat contaminant sampling plans, e.g., anti-inflammatories, antibiotics	Alton et al. (2010); Nienhaus et al. (2017); Peterson et al. (2017)
Animal welfare	Identifying animal welfare issues and assessing the outcomes of efforts to address them. Evaluates compliance with animal welfare standards both on the farm and at the slaughterhouse	Sánchez-Vázquez et al. (2011); Dupuy et al. (2013a); (2013b); (2013c); Vial and Reist (2014); Alton et al. (2015); Eze et al. (2015); Correia-Gomes et al. (2016); (2017); Nienhaus et al. (2017); Guardone et al. (2020); Buzdugan et al. (2021); Alban et al. (2022); Majewski et al. (2022)
Demographic conditions	Assessing different population categories (sex, breed/ production type, age/class, weight, species)	Alton et al. (2012); (2013); (2015); Dupuy et al. (2013a); (2013b); (2013c); (2014); (2015); Haredasht et al. (2018)
Spatial conditions	Show geographic distribution trends of lesions to understand patterns of animal diseases at local, regional, and national levels	Alton et al. (2010); (2012); (2013); (2015); Amezcua et al. (2011); Hernández-Jover et al. (2011); Sánchez-Vázquez et al. (2011); Vial and Berezowski (2014); Vial and Reist (2014); Eze et al. (2015); Correia-Gomes et al. (2016); Peterson et al. (2017); Haredasht et al. (2018); Guardone et al. (2020); Alban et al. (2022); Majewski et al. (2022)
Temporal conditions	Show lesion trends over time to understand patterns of animal disease	Alton et al. (2010); (2012); (2013); Amezcua et al. (2011); Sánchez-Vázquez et al. (2011); Thomas-Bachli et al. (2014); Vial and Berezowski (2014); Eze et al. (2015); Vial et al. (2015); Correia-Gomes et al. (2016); Peterson et al. (2017); Haredasht et al. (2018); Guardone et al. (2020); Alban et al. (2022); Majewski et al. (2022)
Seasonal conditions	Show seasonal trends to understand patterns of animal diseases	Alton et al. (2010); (2012); Sánchez-Vázquez et al. (2011); Vial and Berezowski (2014); Eze et al. (2015); Correia-Gomes et al. (2016); Peterson et al. (2017); Haredasht et al. (2018); Guardone et al. (2020); Alban et al. (2022); Majewski et al. (2022)
Evironmental conditions	Evaluates temperature, rainfall, and humidity conditions related to syndrome occurrence, and assesses the presence of environmental contaminants (e.g., pesticides, insecticides, heavy metals) based on meat contaminant sampling results	Alton et al. (2010); Peterson et al. (2017); Haredasht et al. (2018); Lee et al. (2020); Alban et al. (2022)
Slaughter process conditions	Assess process quality by quantifying the number of organs condemned due to issues such as congestion from poor bleeding, petechiae from improper stunning, aspiration due to inadequate fasting, contamination with bile, pus, urine, feces, or ruminal	Shadbolt et al. (1987); Alton et al. (2013); (2015); Dupuy et al. (2013a); (2013b); (2013c); (2014); (2015); Correia-Gomes et al. (2016); Peterson et al. (2017); Guardone et al. (2020); Buzdugan et al. (2021); Alban et al. (2022)

(*continued on next page*)

Table 2 (*continued*)

Monitoring objective	Considerations	Reference(s)
	content, ingestion, and the presence of foreign objects or substances	
Benchmarking	Comparative assessment of animal health indicators (e.g., morbidity or health status) across farms, slaughterhouses, regions, or countries. It respects local epidemiology, food safety culture, and trade agreements, and is used by industry or authorities to identify risks and improve health outcomes by replicating successful practices	Shadbolt et al. (1987); Eze et al. (2015); Correia-Gomes et al. (2016); (2017); Nienhaus et al. (2017); Guardone et al. (2020); Narita et al. (2024)
Economic conditions	Enable the assessment of economic losses (due to condemnations and reduced productivity) to improve cost—benefit ratios on farms and in slaughterhouses. Authorities may offer support to owners of identified high-risk herds	Shadbolt et al. (1987); Dupuy et al. (2013a); (2013b); (2013c); Neumann et al. (2014); Vial and Reist (2014); Eze et al. (2015); Correia-Gomes et al. (2016); Haredasht et al. (2018)

context specific, and standardization across systems is limited, constraining comparability between studies. Consequently, 64% (39/61) of the variables are qualitative, with this type of syndromic data being the most commonly used in monitoring and surveillance applications, whereas 36% (22/61) of the variables are quantitative. The full classification of the variables and categories analyzed is available in Supplementary Table S4.

The reported strengths of AHSyS are related primarily to timeliness, flexibility, and the capacity to integrate multiple data streams (Fig. 2). Nevertheless, several methodological and operational biases were recurrently identified, including data incompleteness, reporting delays, and limited validation procedures. A comprehensive list of reported strengths and biases is provided in Supplementary Tables S5 and S6.

According to the reviewed studies, several categories of data were consistently excluded during the construction and analysis of slaughterhouse-based AHSyS indicators. These exclusions were driven primarily by limitations related to data representativeness, quality, or relevance to syndromic surveillance objectives. Specifically, excluded data included subpopulations with very small sample sizes (e.g., calves under 8 months, culled boars) (Dupuy et al., 2014; 2015; Peterson et al., 2017); animals that died during ante-mortem inspection (Dupuy et al., 2013c; 2014); records with a high proportion of missing values (Alton et al., 2010; 2012,; Dupuy et al., c); datasets containing inconsistencies (Alton et al., 2010; 2012,; Neumann et al., 2014; Correia-Gomes et al., 2016); farm or animal owner identification data excluded for data protection reasons (Muellner et al., 2015); rare or intermittent lesions (Neumann et al., 2014); conditions related to processing deficiencies (e.g., scalding issues) (Buzdugan et al., 2021); and records affected by incorrect recording or mixed information from animals of different farms within the same batch (Correia-Gomes et al., 2016).

The evaluation of slaughterhouse-based AHSyS included both technical performance attributes (e.g., sensitivity, specificity, response time, and predictability) and user-related factors influencing system adoption and sustainability.

3.1. Sensitivity

In passive surveillance systems, such as slaughterhouse inspections, sensitivity largely depends on the likelihood that clinical signs are recognized and reported, followed by appropriate sample submission (Hernández-Jover et al., 2011; Pineda et al., 2022). Several factors influence this sensitivity, including the level of training among inspectors, stakeholder awareness of disease manifestations, and the degree of standardization in inspection procedures. Additionally, the analytical

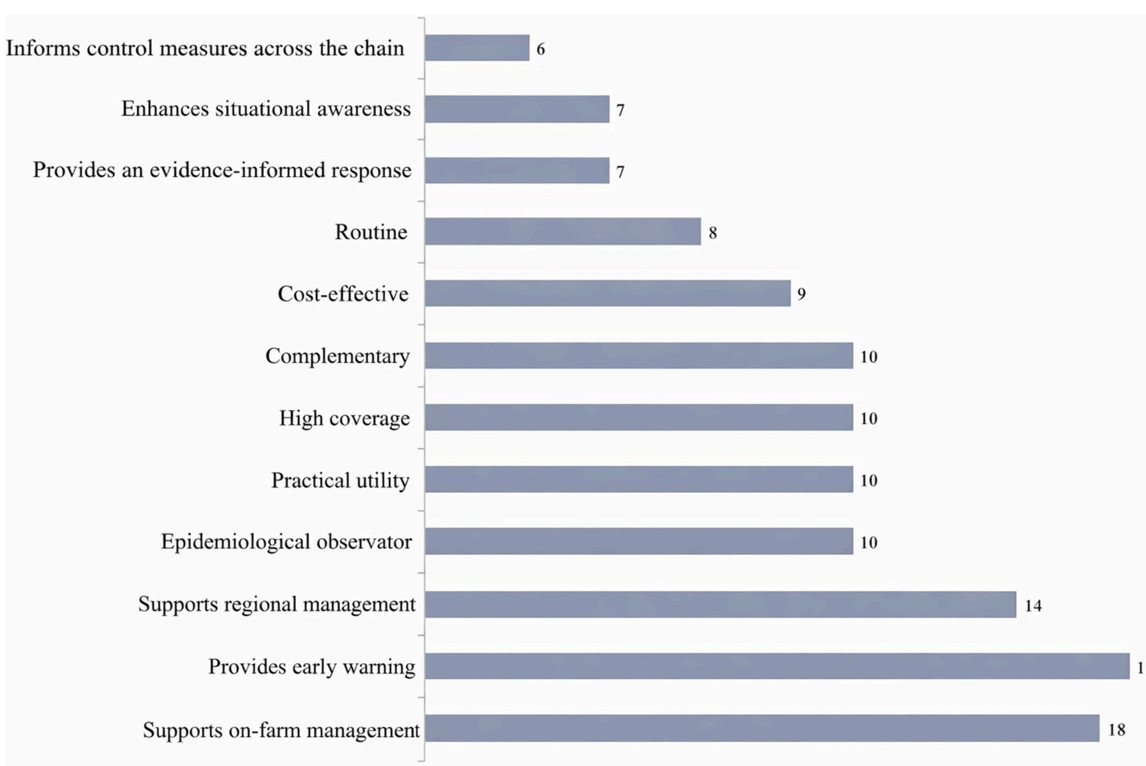

Fig. 2. Frequency of most reported strengths of animal health syndromic surveillance (AHSyS) in slaughterhouses, with contextual considerations, according to the 34 relevant articles included in the scoping review (1987–2024). A single article may address more than one specific topic as its objective.

algorithm used can significantly impact sensitivity. For example, Dupuy et al. (2015) reported the highest sensitivity when a negative binomial algorithm was applied. To estimate sensitivity over time, methods such as scenario trees (Hernández-Jover et al., 2011) and stochastic simulations (e.g., Latin hypercube sampling) are typically employed. While routine meat inspections generally demonstrate low sensitivity, particularly for endemic conditions with low prevalence, more detailed or targeted inspections can markedly increase detection capacity, as shown by Enøe et al. (2003). Improving disease recognition skills among farm personnel and inspectors is also critical for increasing sensitivity across different surveillance points.

3.2. Specificity

This is typically calculated as the proportion of nonoutbreak weeks correctly identified as alarm-free, as opposed to periods with confirmed disease presence during which an alert would be expected. In SyS, specificity is often lower owing to the nonspecific nature of the data, as similar pathological findings may result from a variety of causes. Specificity can be improved through several strategies, including validation with farm- and laboratory-based data, adjustment for confounding factors, and improvements in data quality. Certain datasets, such as those derived from partial carcass condemnations, tend to exhibit greater specificity; however, substantial variability between abattoirs and inconsistencies in coding practices pose challenges to standardization (Enøe et al., 2003; Alton et al., 2010; 2012,; Hernández-Jover et al., 2011; Sánchez-Vázquez et al., 2011; Thomas-Bachli et al., 2012,; Dupuy et al., 2015; Eze et al., 2015; Muellner et al., 2015; Vial et al., 2015; Correia-Gomes et al., 2016; Nienhaus et al., 2017; Haredasht et al., 2018; Lee et al., 2020; Buzdugan et al., 2021; Alban et al., 2022; Pineda et al., 2022). Some studies have noted that specificity may be slaughterhouse-dependent and highly sensitive to how health conditions are classified and recorded, as well as to the analytical algorithms applied. For example, Dupuy et al. (2015) reported greater specificity when a CUSUM algorithm was used than when other methods were used, whereas Enøe et al. (2003) estimated a specificity above 93.3% when a more comprehensive inspection protocol was applied, in contrast to traditional inspection procedures.

3.3. Response times

None of the included studies explicitly evaluated response time as an outcome. However, several authors acknowledged the importance of timely detection and highlighted system features that could facilitate faster responses. While response time was not quantitatively assessed, tools such as AHSyS, along with platforms such as Google Maps and Google Charts, were described as enabling near real-time data visualization and reporting. These functionalities contribute to faster trend recognition and improved situational awareness. The automation of data analysis and visualization processes was also seen as a key factor in reducing reliance on manual workflows, potentially accelerating the detection of abnormal patterns. Nonetheless, expert review and validation remain essential to ensure data quality and the appropriateness of alerts prior to initiating a response.

3.4. Predictivity

Forecasting evaluates a surveillance system's capacity to anticipate disease outbreaks before they occur. Models such as the distributed health risk (DHR) model are typically applied for short- and long-term predictions (e.g., over 3- and 12-month periods), with performance typically assessed via metrics such as the mean relative prediction error (MRPE). The predictive accuracy of SyS can be enhanced by integrating multiple analytical approaches, including Shewhart control charts, CUSUM algorithms, and negative binomial models, as demonstrated by Dupuy et al. (2015). However, the selection of forecasting models must be carefully aligned with the nature of the data and the specific objectives of the surveillance system, whether focused on spatial, temporal, or spatiotemporal dimensions. Arbitrary model selection without adequate validation may lead to inaccurate or misleading results. Therefore, prior testing using simulated or historical outbreak data is essential to ensure reliability. Moreover, the inclusion of relevant covariates is critical to improve model performance and reduce bias in interpretation. Simulated scenarios have shown that delays in detection remain a considerable challenge, with more than 50% cases occurring before the system is able to issue an alert, as evidenced by Vial et al. (2015).

3.5. Social knowledge, perception, and attitudes

Since 1987, stakeholders have acknowledged the potential value of slaughterhouse surveillance data for monitoring animal health conditions such as pneumonia, arthritis, and intestinal infections. However, persistent challenges limit their practical use. Key barriers include inconsistent application of diagnostic codes, insufficient training of inspection personnel, difficulties in recording data during high-speed processing, unclear reporting formats, and limited integration with laboratory tools. The communication gaps between slaughterhouses, veterinarians, and producers remain widespread; many producers report never discussing slaughter findings with their veterinarians, a disconnect often attributed to habits, perceived irrelevance, or unclear data presentation. Producers with higher education levels or who manage breeding operations tend to place greater value on slaughter data, particularly when it is provided frequently and in detail, and generally support sharing it with their own veterinarians while remaining hesitant about third-party access. Improving training, data presentation, and system usability are therefore critical steps toward ensuring that slaughterhouse data are effectively applied in health-related decision-making (Shadbolt et al., 1987; Neumann et al., 2014; Vial and Berezowski, 2014; Correia-Gomes et al., 2016; Alban et al., 2022; Pineda et al., 2022).

The statistical analytical techniques used are summarized in Table 3. Among the included studies, pigs (n = 19) and cattle (n = 10) were the most studied species. Most studies were retrospective in design, used individual animals as the epidemiological unit, and relied on postmortem inspection data. Monthly temporality predominated in cattle studies, whereas quarterly temporality was more common in pig studies. The detailed system characteristics by species are presented in Table 4. The core syndromic classifications showed partial convergence across systems, although substantial heterogeneity persisted (Table 5).

Total carcass condemnation (WCC) is typically associated with acute or systemic infections such as septicemia, toxemia, cachexia, jaundice, and neoplasms (Dupuy et al., 2014; Thomas-Bachli et al., 2014). In contrast, partial carcass condemnation (PCC) is more commonly linked to localized or chronic infections, including pneumonia, parasitic liver lesions, arthritis, and nephritis (Vial and Reist, 2015; Alban et al., 2022). Some studies have adopted a multifactorial health monitoring approach, using cluster analysis or expert weighting to group lesions into thematic “focus areas”, such as respiratory health, animal handling, or external injuries (Peterson et al., 2017). This strategy enhances interpretation by enabling a more integrated understanding of animal health status across different conditions. However, international disparities persist. The level of detail and application of condemnation codes vary considerably across countries and surveillance systems, which complicates direct data comparison and benchmarking (Correia-Gomes et al., 2017; Alban et al., 2022).

The implementation of AHSyS systems in slaughterhouses varies widely across countries, reflecting differences in infrastructure, surveillance objectives, data accessibility, and integration with national health programs. Despite these differences, several systems stand out owing to their scope, operational continuity, and contributions to animal health monitoring and policy development.

Table 6 provides an overview of the most representative AHSyS

Table 3
Statistical analytical techniques used in the 34 relevant articles on animal health syndromic surveillance (AHSyS) in slaughterhouses included in the scoping review (1987–2024), with contextual considerations.

Category	Level of use *	Considerations
Regression and multilevel models	High	All types of regression analyses (linear, logistic, Poisson, and negative binomial), as well as mixed and multilevel models. Common methods include Generalized Linear Models (GLM), Generalized Linear Mixed Models (GLMM), logistic/multinomial regression, random effects models, and hierarchical modeling frameworks
Descriptive, inferential statistics and model evaluation	Intermediate	Encompasses classical statistical techniques, hypothesis testing, and model performance criteria. This includes descriptive statistics, Pearson and Spearman correlations, ANOVA, Chi-square tests, Kruskal–Wallis tests, model selection criteria such as AIC (Akaike Information Criterion), BIC (Bayesian Information Criterion), and QIC (Quasilikelihood under the Independence Model Criterion), ROC curves, Kappa statistics, goodness-of-fit assessments, cross-validation procedures, and Monte Carlo simulations
Time series and dynamic models	Intermediate	Refers to methods tailored for longitudinal or time-dependent data analysis. Techniques include ARIMA (AutoRegressive Integrated Moving Average), SARIMA (Seasonal ARIMA), Generalized Additive Models (GAM) and other semiparametric additive models, state-space models, random walk models, harmonic regression, and outbreak detection tools such as EWMA (Exponentially Weighted Moving Average), CUSUM (Cumulative Sum Control Chart), and the Farrington algorithm
Spatial and multivariate analysis	Intermediate	Focus on multidimensional or geographically distributed data. This includes spatial analysis methods (e.g., scan statistics, Haversine distance), Multiple Factor Analysis (MFA), K-means clustering, hierarchical clustering, Multidimensional Scaling (MDS), Redundancy Analysis (RDA), PERMANOVA (Permutational Multivariate Analysis of Variance), bipartite network analysis, and specialization indices
Advanced and Bayesian approaches	Low	Covers methods based on Bayesian inference, latent class models, and advanced simulation-based frameworks. These include Gibbs sampling, prior/posterior analysis, decision trees and scenario trees, and sensitivity analysis
Uncategorized	Low	Not applicable

[*] High: 25–30 articles (74–89%); Intermediate: 9–25 articles (25–73%); Low: ≤ 8 articles (<25%).

Table 4
Target animal species addressed in the 34 relevant articles on animal health syndromic surveillance (AHSyS) in slaughterhouses included in the scoping review (1987–2024).

Species (articles n)	Pigs (19)	Cattle (10)	Various (3)	Poultry (1)
System status[1]				
Not reported	16	9	3	1
Active	2	1	0	0
Not active	1	0	0	0
Inspection				
Both	9	4	0	0
Post-mortem	7	4	1	1
Ante-mortem	2	0	2	0
Not reported	1	2	0	0
Temporality				
Daily	2	1	0	0
Weekly	4	1	0	0
Monthly	5	8	2	1
Quarterly	3	0	0	0
Annually	2	0	0	0
Not reported	3	0	1	0
Direction				
Retrospective	12	7	1	1
Retrospective and	4	3	1	0
predictive	1	0	0	0
Retrospective and	2	0	1	0
prospective				
Not applicable				
Epidemiological unit				
Individual	14	10	2	0
Batch	4	0	0	1
Not reported	1	0	1	0
Other	0	0	0	0
Analyzed condemnation				
WCC	5	3	2	0
PCC	6	3	0	0
Both	7	4	0	1
Not reported	1	0	0	0
Value				
Proportion	8	8	1	0
Frequency	4	2	1	0
Average	0	0	0	0
Percentage	5	0	0	1
Other	1	0	0	0
Not reported	1	0	1	0
Considered syndromes	15	5	1	1
Cause	0	2	0	0
Organ	0	0	0	0
System	0	2[3]	0	0
Several	2[4]	0	0	0
Other	2	1	2	0
Not reported				
System users				
Government	7	6	1	0
Academy	0	2	1	0
Slaughterhouses	0	0	0	0
Clients	0	0	0	0
Private sector	0	0	0	0
Several	0	0	0	0
Not reported	12	2	1	1

WCC=Whole condemnation carcass; PCC=Partial condemnation carcass; AI=Artificial intelligence.
[1]In the moment of the study
[2]Trained operator
[3]Organ and cause
[4]Classical swine fever, Foot and mouth disease

systems globally, highlighting their key characteristics and operational features. To harmonize or analyze the aforementioned syndromic codes, the first step is to map all unique conditions to a controlled vocabulary (e.g., terms aligned with CDC or OMSA disease codes). Next, the conditions should be categorized into high-level syndrome groups for statistical analysis or surveillance purposes (e.g., respiratory infection, systemic, and management-related). Finally, overlaps and divergences between data harmonization systems or meta-analyses should be identified and documented.

The successful implementation of an AHSyS system based on slaughterhouse data requires a structured and multisectoral approach. The following figure (Fig. 3) outlines the main technical and operational steps involved, from early preparatory actions to continuous improvement. Each step is supported by the relevant literature and emphasizes the importance of data quality, stakeholder collaboration, and strategic

Table 5
Core syndromic classifications in global animal health syndromic surveillance (AHSyS) in slaughterhouses, according to the 34 relevant articles included in the scoping review (1987–2024).

Syndromic category	Included conditions	Associated systems/codes and notes
Respiratory	Pneumonia, pleurisy, pericarditis, pleuropneumonia, lung abscesses	Used in BPHS, WPS, NI, Germany, Finland, Denmark (Eze et al., 2015; Correia-Gomes et al., 2017; Alban et al., 2022)
Digestive/ hepatic	Liver spots (ascariasis), parasitic liver, peritonitis, enteritis, fascioliasis	Included in UK, Germany, Finland (Alban et al., 2022); "parasitic liver" may include fibrosis and necrosis (Alton et al., 2013).
Septicemia/ generalized infections	Pyemia, septicemia, toxemia, cachexia, multiple abscesses, jaundice, erysipelas	Linked to total condemnations (WCC); emphasized by USDA and Germany (Dupuy et al., 2014; Thomas-Bachli et al., 2014; Alban et al., 2022).
External lesions/ handling	Tail bites, ear lesions, arthritis, bruises, dermatitis, bursitis	Key in welfare systems like Finland and Denmark (Alban et al., 2022); monitored at the slaughterhouse level
Systemic/ nonspecific	Emaciation, jaundice, tumors, nephritis, edema, chemical residues (antibiotics, heavy metals)	Present in USDA and German systems (Alton et al., 2010; Majewski et al., 2022); some syndromes lack sufficient data for analysis (Peterson et al., 2017).
Meat quality defects	Abnormal color, odor, texture, heat damage, contamination, congestion	Classified in WCC/PCC and USDA-style coding systems (Vial and Reist, 2015; Guardone et al., 2020).
Parasitic conditions	Cysticercosis, sarcocystosis	Classified as PCC or WCC depending on severity (Vial and Reist, 2015)
Topographic (by organ)	Lung, liver, kidney, heart, lymphatic lesions. Partial carcass condemnations (PCC) often reflect localized or chronic conditions (e.g., pneumonia, parasitic liver, nephritis, arthritis)	Germany and some Finnish systems use an anatomical coding approach (Alban et al., 2022)
Other specific conditions	Mastitis, carcinoma, rabies, tuberculosis, classic swine fever (CSF)	Not always sufficient for time-series analyses (Alton et al., 2010; Neumann et al., 2014; Majewski et al., 2022).

decision-making. A dedicated figure has been included to illustrate and summarize these elements in greater detail, providing a visual reference that complements the narrative synthesis (Supplementary Figure S1).

4. Discussion

This ScR provides an integrated synthesis of the global evidence on slaughterhouse-based animal health syndromic surveillance systems, revealing a field characterized by methodological diversity, uneven geographical development, and limited standardization. Rather than reflecting a mature and harmonized surveillance approach, the identified literature highlights substantial heterogeneity in system design, data sources, syndromic classifications, and analytical methods, which constrains comparability across settings.

Despite this variability, consistent cross-cutting patterns emerged regarding the primary purposes of these systems—namely, early disease detection, monitoring of animal health and welfare, and support for epidemiological investigations—emphasizing the strategic value of slaughterhouses as a population-level surveillance point. Moreover, recurrent gaps related to validation, data quality, and integration with other surveillance streams point to critical areas requiring further development to advance standardization and effective implementation.

One of the most pervasive dimensions of this heterogeneity relates to how syndromic surveillance is conceptualized and labeled across studies.

Despite an overall increase in research activity over the past two decades, the total number of included studies remains limited, and significant variability persists in the terminology and conceptual frameworks used. While the concept of "*syndromic surveillance*" has gained prominence, several studies describe approaches aligned with AHSyS principles without explicitly using this terminology. This lack of terminological standardization and conceptual clarity complicates evidence synthesis, limits comparability across studies, and underscores the need for more consistent definitions and methodological alignment in future research.

From a methodological perspective, the performance of slaughterhouse-based AHSyS remains highly context dependent and insufficiently validated across studies. Sensitivity and specificity are consistently influenced by inspection practices, data quality, coding systems, and analytical choices rather than by inherent system capacity. While several studies have explored outbreak detection performance via simulated scenarios or historical data, formal validation against independent reference standards is uncommon, and the methods used vary widely (Enøe et al., 2003; Hernández-Jover et al., 2011; Dupuy et al., 2015; Eze et al., 2015; Muellner et al., 2015; Alban et al., 2022).

A particularly critical and underappreciated source of variability in slaughterhouse-based AHSyS lies in the lack of harmonization of meat inspection data at the two levels. At the international level, countries do not share standardized code lists for recording post-mortem findings, making direct cross-country comparisons methodologically problematic. At the intranational level, meat inspectors frequently develop plant-specific conventions regarding when and how to register a finding, introducing substantial between-plant variation that is independent of true differences in animal health status. This dual source of inconsistency severely limits the utility of meat inspection data for surveillance purposes. This limitation has motivated the development of computer vision and automated image analysis systems, which aim to reduce observer-dependent variability by standardizing the detection and recording of lesions (Sandberg et al., 2023).

Despite its utility, slaughterhouse-based SyS also presents several methodological, technical, and institutional limitations that may affect the quality and applicability of the data collected. Key challenges include multiple sources of bias, such as selection bias, underreporting, observation and information bias, population and spatiotemporal bias, reporting delays, and over aggregation (ecological fallacy). These issues can distort the interpretation of findings and reduce their value for population-level surveillance. Additionally, low specificity and sensitivity for certain syndromes, variability in data quality, and inconsistent case definitions hinder comparability across slaughterhouses or regions.

Response time and predictive capacity are rarely evaluated as explicit outcomes, despite being central objectives of syndromic surveillance. Although automated algorithms, visualization platforms, and forecasting models (e.g., CUSUM, negative binomial models, and scenario trees) have been reported to enhance early signal detection (Dupuy et al., 2015; Vial et al., 2015), delays in alert generation and challenges in distinguishing true signals from noise remain common. Collectively, these findings indicate that methodological robustness and validation constitute major bottlenecks preventing slaughterhouse-based AHSyS from evolving beyond exploratory tools into reliable, decision-support surveillance systems.

In addition to technical performance, the effectiveness and sustainability of slaughterhouse-based AHSyS are strongly shaped by human, institutional, and usability-related factors. Across studies, producers and veterinarians have generally recognized the potential value of slaughterhouse data for monitoring animal health and welfare; however, a limited understanding of condemnation causes, insufficient training, and unclear data presentation have reduced practical use (Shadbolt et al., 1987; Neumann et al., 2014; Correia-Gomes et al., 2016; Alban

Table 6
Key characteristics of the most representative slaughterhouse-based animal health syndromic surveillance (AHSyS) systems worldwide, according to the 34 relevant articles included in the scoping review (1987–2024).

Country/ System	Focus	Coding	Strengths	Limitations	Reference(s)
Canada	Official veterinary inspection focused on food safety, with growing interest in animal health and welfare surveillance	Structured classification by lesion and affected organs (e.g., pneumonia, pleurisy, abscesses, parasitic liver). Total or partial condemnations are applied (similar to WCC/PCC). Some provincial programs supplement with welfare monitoring	Regulated by the Canadian Food Inspection Agency (CFIA). High food safety standards and integration with export certifications	Limited use of data for systematic population-level surveillance; data not always standardized across plants	Alton et al. (2010); (2012); (2013); (2015); Amezcua et al. (2011); Thomas-Bachli et al., (2012); (2014)
United Kingdom	Epidemiological surveillance focused on monitoring endemic diseases and subclinical conditions in pigs	Focuses on respiratory, hepatic, skin/tail, and septic conditions. Codes are often used for epidemiological surveillance. List of 11–12 main conditions (e.g., pneumonia, pleuritis, abscesses, pyemia, peritonitis, tail damage)	Comparable historical data; useful for producer feedback. Coverage includes: BPHS (England and Wales), WPS (Scotland), NI (Northern Ireland)	Limited to specific conditions; focused inspection	Sánchez-Vázquez et al. (2011); Eze et al. (2015); Correia-Gomes et al. (2016); (2017); Lee et al. (2020); Buzdugan et al. (2021)
France	Veterinary public health and animal traceability	Centralized system (SIGAL, RASVE), integrates post-mortem findings with individual animal ID. Includes classification by organ and etiology (e.g., abscesses, cysticercosis, pericarditis)	Strong IT infrastructure: data used in epidemiological studies	SyS use is still in pilot or early implementation phase	Dupuy et al. (2013a); (2013b); (2013c); (2014); (2015)
Germany	Nationally regulated health surveillance with flexible slaughterhouse-level integration	Standardized national system with separate codes for organ findings and carcass-level lesions. Includes detailed codes for organs/tissues and systemic conditions	High detail level and compatibility with control programs	Complexity can hinder syndromic data aggregation and comparison	Nienhaus et al. (2017); Alban et al. (2022)
Denmark	Integrated system for sanitary inspection and animal welfare monitoring	Classified into six groups (e.g., topographic, etiological, contamination, residues). Determines regulatory actions such as freezing, deboning, or rejection	High traceability: syndromic coding linked to regulatory actions. Distinguishes between mandatory reportable codes and slaughterhouse-specific tracking codes	Strong technical approach, but may not capture complex multifactorial syndromes	Enøe et al. (2003); Alban et al. (2022)
United States (USDA-style)	Food safety based on meat fitness rather than epidemiological surveillance	Broad list (35–36 + conditions), classified into WCC or PCC. Emphasis on lesion severity and systemic nature	Highly standardized; useful for public risk control	Limited resolution for population analysis or syndrome-specific monitoring	Peterson et al. (2017); Haredasht et al. (2018)
Finland	Animal welfare evaluation and systematic population-level surveillance	National list combined with internal slaughterhouse codes. Monitors seven key conditions: abscesses, arthritis, ascariasis (liver spots), pericarditis, pleuritis, pneumonia, and tail biting	Strong welfare indicator focuses; integrates with production data. Distinguishes between mandatory reporting and plant-specific monitoring codes	Focused on prevalent conditions; less suitable for emergencies	Alban et al. (2022)
Australia	Animal health, food safety, and trade support through post-mortem inspection and species-specific monitoring programs	Classification based on anatomical and etiological findings (e.g., abscesses, pneumonia, liver lesions, pleuritis). Some states also record welfare-related findings	Links veterinary inspection with public health and export programs. Established as National Animal Health Monitoring System (NAHMS)	Uneven use across regions; limited integration with real-time automated SyS systems	Hernández-Jover et al. (2011)

PCC=Partial carcass condemnation; SyS=Syndromic surveillance; WCC=Whole carcass condemnation.

et al., 2022; Pineda et al., 2022).

Persistent communication gaps between slaughterhouses, veterinarians, and producers further constrain system uptake. Concerns regarding data reliability, inconsistent coding, high-speed processing constraints, and limited benchmarking mechanisms undermine trust and user engagement (Vial and Berezowski, 2014; Correia-Gomes et al., 2016; Alban et al., 2022). Although stakeholders generally support the use of slaughterhouse data when confidentiality and relevance are ensured, hesitancy toward data sharing with third parties and the absence of clear governance frameworks limit broader integration into national surveillance systems.

Despite these challenges, slaughterhouse-based AHSys present several strengths that position them as strategic components of modern animal health surveillance. Their routine implementation, cost-effectiveness, and broad population coverage enable continuous monitoring of animal health and welfare at scale. When appropriately integrated, these systems can enhance situational awareness, support early warning functions, and inform decision-making across the agri-food chain while offering opportunities for automation, traceability, and alignment with One Health frameworks.

Conversely, multiple structural and institutional limitations persist, including heterogeneous infrastructure, inconsistent coding practices, limited traceability to the farm of origin, and the absence of harmonized surveillance protocols. These constraints, coupled with insufficient economic evaluations and unclear designation of sentinel slaughterhouses, restrict system scalability and comparability across contexts. Addressing these issues will require coordinated investments in training, standardized data frameworks, and formal system validation.

Slaughterhouse-based AHSyS offers substantial opportunities for future development, particularly through integration with emerging technologies such as artificial intelligence, automated image analysis, and geographic information systems. Advancing international harmonization of syndromic definitions and codes would facilitate cross-country comparisons, regional early warning systems, and more effective data sharing. Moreover, expanding these systems within One Health frameworks could increase the detection of zoonoses, antimicrobial

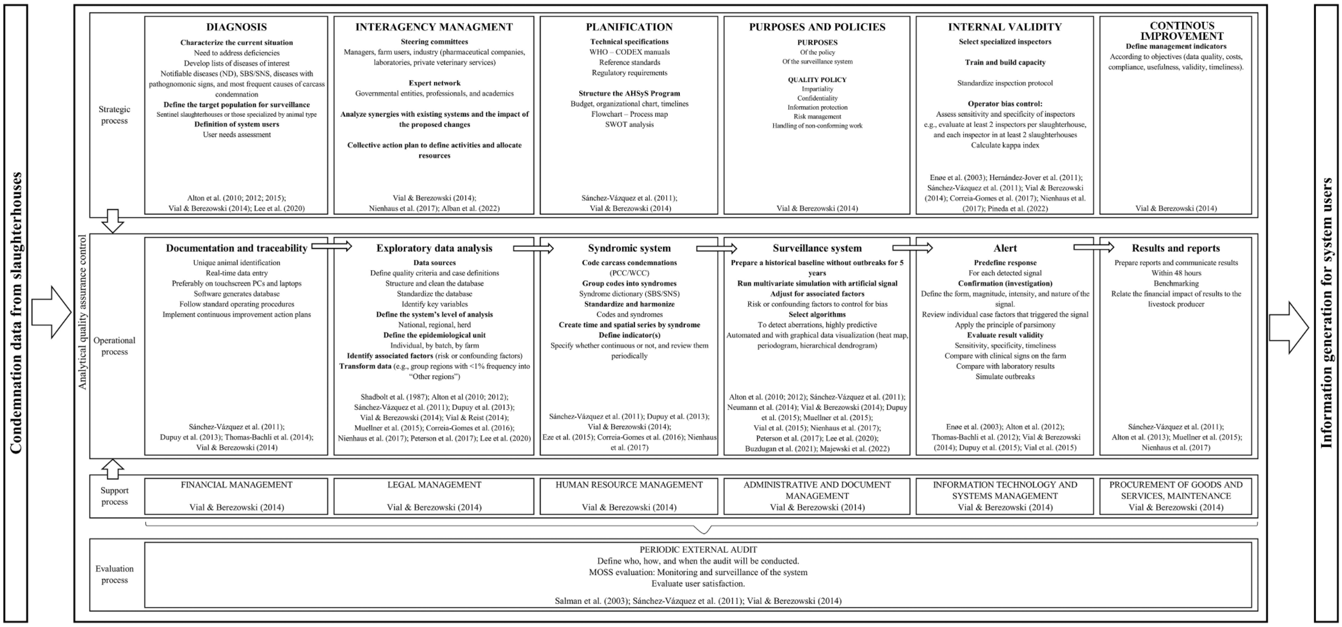

Fig. 3. Proposed key steps for the implementation of a slaughterhouse-based animal health syndromic surveillance (AHSyS) system, considering findings from the 34 relevant articles included in the scoping review (1987–2024).

resistance, chemical hazards, and animal welfare concerns.

Despite their potential, several threats may compromise system sustainability, including limited political commitment, funding constraints, resistance to technological change, and fragmented institutional responsibilities. Technical challenges related to data validity, coverage, and representativeness, along with unclear legal and ethical frameworks governing data use, may further undermine system credibility and uptake if not adequately addressed.

Compared with other animal health surveillance approaches, slaughterhouse-based animal health syndromic surveillance systems present a distinct combination of advantages and limitations. Unlike laboratory-based surveillance or formal clinical reporting systems, which rely on diagnostic confirmation and are often subject to reporting delays, slaughterhouse-based AHSyS operates continuously and generates large volumes of routinely collected, population-level data. This enables earlier detection of abnormal patterns and broader situational awareness across production systems. However, the nonspecific nature of post-mortem indicators, variability in inspection practices, and differences in data quality constrain diagnostic precision and may limit responsiveness to specific events. These characteristics underscore the complementary role of slaughterhouse-based AHSyS within integrated surveillance architecture rather than their use as standalone systems.

Within integrated surveillance frameworks, the added value of slaughterhouse-based AHSyS lies in its ability to enhance early warning, support hypothesis generation, and inform risk-based prioritization when combined with confirmatory data streams. Their effectiveness is maximized when slaughterhouse data are systematically linked with farm-level information, laboratory diagnostics, and field surveillance, allowing for the triangulation of signals and more robust interpretation. Consequently, the contribution of slaughterhouse-based AHSyS should be evaluated not in isolation but in terms of how effectively it complements existing systems, reduces information gaps, and supports coordinated decision-making across the animal health, food safety, and One Health domains.

This ScR was conducted via a transparent and reproducible methodology, following PRISMA-ScR guidelines, with a comprehensive search strategy across multiple databases and conference proceedings and structured tools for relevance screening, study characterization, quality appraisal, and data extraction, allowing for consistent synthesis despite substantial heterogeneity in study designs, data sources, and analytical approaches. Limitations include the nonretrieval of two relevant documents (Weber, 2012; Dupuy et al., 2013b), incomplete gray literature coverage, and subscription barriers that may have introduced omission bias, partially mitigated through snowballing and citation tracking. Like with all the ScRs, formal quantitative comparisons or meta-analyses were not possible; therefore, the findings should be interpreted as a descriptive and integrative overview rather than an assessment of effect size or system performance.

5. Conclusion

Slaughterhouse-based syndromic surveillance represents a valuable and complementary component of animal health surveillance systems, with demonstrated potential for early warning, population-level monitoring, and support of One Health approaches. While slaughterhouse-derived data offer advantages related to coverage, cost-effectiveness, and routine availability, their effective use remains constrained by limited standardization, variable data quality, insufficient epidemiological validation, and challenges in data traceability and integration. Advancing this field will require coordinated efforts to harmonize syndromic codes, strengthen methodological validation, integrate emerging technologies, and embed these systems within interoperable national and international surveillance architectures.

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Quiroga-Robayo Mayra Alejandra: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nathalia M. Correa-Valencia:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Fernanda C. Dórea:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used OpenAI ChatGPT (October 2023 version, https://chat.openai.com/) to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.prevetmed.2026.106940.

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