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Risk Assessment Methodologies for Imports of Products of Animal Origin: A Systematic Review of Formal and Informal Trade Pathways

Aya Attia Koraney Zarea
Istituto Zooprofilattico Sperimentale delle Regioni Lazio e Toscana
Giovanni Brajon
Istituto Zooprofilattico Sperimentale delle Regioni Lazio e Toscana
Beate Conrady
University of Copenhagen
Laura C. Gonzalez Villeta
Animal and Plant Health Agency
Clazien J de Vos
Wageningen University & Research
Roberto Condoleo
roberto.condoleo@izslt.it

Istituto Zooprofilattico Sperimentale delle Regioni Lazio e Toscana

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Abstract

The international trade of products of animal origin (POAO) represents an important pathway for the introduction of transboundary animal diseases (TADs). Import risk assessments (IRAs) are widely used to evaluate this risk; however, approaches vary considerably depending on the type of commodity, trade pathway, and data availability. This study systematically reviewed published IRAs to examine the frameworks, methodologies, data sources, and disease–commodity combinations used to assess risks associated with both formal (legal) and informal (illegal) trade of POAO.

Out of 2,541 records, a total of 50 records met the inclusion criteria for this systematic review, describing a total of 51 different import risk assessment studies. The most widely adopted and internationally recognised frameworks were included, representing a range of analytical methodology, including qualitative, semi-quantitative, and fully quantitative approaches. Across all eligible studies, there was a strong focus on the early stages of the risk pathway, particularly entry assessment (45%), while the remaining studies (55%) evaluated the entry phase combined with exposure, consequences, or subsequent spread. The most studied viruses were african swine fever virus (ASFV) (n = 19, 37%), foot-and-mouth disease virus (FMDV) (n = 17, 33%), and classical swine fever virus (CSFV) (n = 8, 16%), highlighting their global impact on livestock production and trade. Meat and meat products were the most frequently evaluated commodities (n = 39, 76%), particularly those derived from pigs and cattle, and were often linked to high-risk pathways, such as passenger-mediated transport of contaminated products and informal cross-border trade. In contrast, milk and dairy products were less frequently assessed (n = 9, 18%), while commodities such as bushmeat and fish products were only rarely considered. Formal trade pathways dominated the literature due to the availability of structured data, while informal trade was less frequently assessed despite being recognised as an important route for disease introduction. Informal pathways mainly involved passenger transport of products in personal luggage, while other pathways, such as postal consignments or courier shipments, received little attention. These findings highlight gaps in current IRA studies, particularly regarding informal trade. Addressing these gaps will require stronger surveillance and monitoring systems, improved reporting of informal product movements, and greater international collaboration to support more realistic and comprehensive risk assessments.

Introduction

The global movement of animals and products of animal origin (POAO) plays an important role in the risk of the introduction of infectious animal diseases into previously free countries or regions. Among these diseases, transboundary animal diseases (TADs) pose a significant concern for animal health authorities due to their ability to spread rapidly across borders and their economic and social impacts, including large-scale animal culling, disruptions in livelihoods and food security, trade restrictions, and significant costs associated with disease control and eradication programs [1–6]. Therefore, sufficient sanitary and phytosanitary (SPS) measures must be implemented to mitigate the risk of TADs incursion through trade. However, compliance with the World Trade Organization (WTO) Agreement on the

Application of Sanitary and Phytosanitary Measures (“The SPS Agreement”) [7] does not eliminate the risk entirely, and outbreaks of exotic diseases may still occur, resulting in substantial economic and production losses.

Among the various pathways for the international spread of animal pathogens, POAO have been identified as a potentially significant pathway for pathogen introduction. During systemic infections, such as viremia or bacteremia, pathogens can disseminate throughout the animal and colonize tissues and organs, such as skeletal muscle, that are commonly consumed by humans. Consequently, the presence of infected animals into the food production chain may lead to the distribution of contaminated products across domestic and international markets [8]. To prevent clinically infected animals from entering the food chain, official veterinary services are present at farms and slaughterhouses to conduct ante and post mortem inspections. However, some of these animals may be in the incubation period of infection, during which pathogens can be present in tissues, organs, or secretions without causing detectable clinical signs. As a result, products derived from these animals may be contaminated and enter the food production chain unnoticed [9].

The risk associated with POAO is closely linked to the ability of pathogens to survive in animal-derived products. Survival of pathogens outside the host depends on several factors, including the physical and chemical properties of the food itself, such as pH and water activity, alongside the environmental conditions during storage and transport. For example, thermal treatments, including cooking and pasteurization, can effectively inactivate many pathogens. However, other preservation methods, such as curing or fermentation, may not ensure complete inactivation [10]. For instance, African swine fever virus (ASFV) can persist in pork and pork products for a long time. The virus has been shown to survive for several months in chilled meat and for years in frozen products [11]. Similarly, foot-and-mouth disease virus (FMDV) can remain viable in animal tissues and dairy products for a long period, especially under favourable pH conditions during refrigeration or freezing storage [12].

Pathogen incursion into disease-free countries can result from the formal and informal movement of animal products. Formal pathways involve officially authorized trade conducted under veterinary supervision and in compliance with national and international sanitary regulations. This includes the commercial importation of animal products such as meat and meat products, milk and dairy products, eggs, and animal by-products [13]. These products are typically accompanied by health certificates and are subject to veterinary inspection at border control points. However, a degree of risk remains, particularly when pathogens are present but undetected in transport containers and are able to survive processing or storage conditions. In contrast, informal pathways operate outside official control systems and will therefore bypass veterinary inspection and certification procedures. These pathways may include the smuggling of meat and animal products, the transport of food items in passenger luggage or postal parcels, informal cross-border trade, and the improper disposal of international catering waste from aircraft or ships. Although difficult to monitor and quantify, such pathways may represent an important route for pathogen introduction, especially when products originate from regions affected by TADs [13].

Given the variety and complexity of these introduction pathways, import risk assessment (IRA) has become a crucial safeguarding tool for evaluating the likelihood and potential consequences of pathogen introduction through the movement of POAO. Over the past few decades, many studies have used qualitative, semi-quantitative, and quantitative risk assessment methods to estimate the likelihood of introduction of animal pathogens related to the formal and informal trade of POAO [14, 15]. These assessments are generally conducted within internationally recognised frameworks, particularly those developed by the World Organisation for Animal Health (WOAH), which include hazard identification, entry assessment, exposure assessment, consequence assessment, and risk estimation.

Although several recent systematic reviews have examined veterinary risk assessment methodologies, none of these have specifically synthesised IRA studies that focused on POAO while simultaneously comparing formal and informal trade pathways. Marques et al. (2025) [16] reviewed quantitative risk assessments (QRA) and concluded that most of these focused on TADs such as FMD, rabies, lumpy skin disease (LSD), and ASF in animal populations. These studies predominantly applied stochastic modelling approaches, commonly based on scenario-tree frameworks and methodologies aligned with the WOAH, with key assumptions often informed by expert elicitation. Horigan et al. (2023) [17] reviewed qualitative risk assessments and reported that several structured tools have been developed to support transparent and robust qualitative assessments, including approaches that incorporate formal reasoning to account for uncertainty.

This systematic review aims to provide a comprehensive overview of IRA studies conducted to evaluate the introduction of animal diseases into countries or regions through formal and informal trade of POAO intended for human consumption. Particular emphasis is placed on the frameworks and methodologies applied (quantitative, semi- quantitative and qualitative), the commodities and pathogens assessed, the trade pathways considered, and the data sources used to support these assessments.

To address this objective, the review was guided by the following research questions:

Primary Research Question

RQ1. What import risk assessment (IRA) frameworks and methodological approaches (qualitative, semi-quantitative, and quantitative) have been applied to assess the risk of disease introduction associated with the formal (legal) and informal (illegal) trade of products of animal origin (POAO)?

Secondary Research Questions

RQ2. Which components of the risk pathway (entry, exposure, establishment, spread, and consequence assessment) are evaluated in the included studies?

RQ3. Which POAO commodities, trade pathways (e.g., formal or informal), trade sub-pathway (e.g., passenger-carried products, smuggled products), and pathogens have been assessed, and how frequently are they reported?

RQ4. What data sources (e.g., surveillance systems, trade databases, expert elicitation, and scientific literature) are used to parameterize IRA models?

Material and Methods

Search Strategy

The systematic review protocol was developed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [18]. To identify relevant literature with a focus on import risk assessment considering POAO, a comprehensive search was conducted on 1st April 2025 across multiple electronic databases, including PubMed (https://pubmed.ncbi.nlm.nih.gov), Web of Sciences (https://apps.webofknowledge.com/), and Scopus (https://www.scopus.com) without time restriction. The search strategy was developed using a combination of keywords and their MeSH terms with Boolean operators (OR and AND) to maximize the retrieval of pertinent studies. The full search strings used are reported in Table 1.

This comprehensive search strategy was designed to find studies describing IRA frameworks and methodological approaches used to assess disease risks associated with the formal and informal trade of POAO. All retrieved records were exported, and duplicates were removed. Titles and abstracts were screened against predefined inclusion and exclusion criteria (Table 2) using the online systematic review platform Rayyan [19]. Full-text screening of eligible articles was subsequently performed independently by two reviewers to assess their relevance to the scope of the review. Discrepancies were resolved through discussion, and when consensus could not be reached, a third reviewer was consulted.

To further enhance study retrieval, the reference lists of all included articles were manually screened to retrieve additional relevant publications. In addition, a structured search and selection strategy for grey literature was implemented to increase the probability of finding eligible non-peer-reviewed documents, including reports from international organisations, national authorities, and institutional risk assessment organizations (Supplementary Table 1).

Data Extraction

Two authors extracted the relevant data from the included articles using a standardised Excel sheet (Microsoft Excel®, Version 2016). For each included study, the following information was extracted:

1. Study publication details: title, authors, year of publication.

2. Risk assessment methodology approach:

- Reference framework or guidelines applied (e.g., World Organisation for Animal Health standards).
- Methods used: qualitative, semi-quantitative, or quantitative; if quantitative specification of stochastic or deterministic modelling.

- Data sources: the type of data source used (e.g., peer-reviewed literature, expert opinion, institutional or surveillance data) for prevalence estimates, trade volumes, seizure data, pathogen survival and dose-response.
- Hazard identification: identified as biological agent in, or a condition of, a good with the potential to cause an adverse health effect [20, 21].

3. Trade-related metadata:

- Importing and exporting country or region
- Trade type (formal or informal)
- Trade sub-pathway
- Type of POAO involved

All the included pathogens in these articles and the number of studies covered by them are listed in Supplementary Table 2. The pathogens that were assessed in only one risk assessment (RA) were grouped under the category “other pathogens” to facilitate the presentation of the result.

To ensure terminological consistency and facilitate comparison across the literature, informal trade pathways were categorized by mode of movement: (i) passenger-mediated transport, covering POAO in personal luggage via air, land, or sea; (ii) postal and courier services; (iii) informal trade, referring to undeclared or incorrectly declared commercial consignments not reported to the competent authorities and the veterinary control system; and (iv) unspecified informal where no specification of the pathway is provided. In case where all the sub-pathways were addressed, we classified them as ‘all pathways’. For formal trade, pathways were classified as trade via seaports, or land borders, all pathways, or unspecified.

POAO data were extracted as reported and standardised for comparative analysis. Products were first grouped by animal species (e.g., pig, bovine, poultry, small ruminants, wild boar, other wildlife species, or aquatic) and, where data permitted, further categorized by product type, such as meat, dairy, and their-products. Assessments involving multiple species were coded as multiple species, while those with insufficient detail were labelled as unspecified.

1. Risk assessment characteristics:

- Intended use of the IRA: policy support, border control, emergency preparedness, and surveillance prioritisation. More details are presented in Supplementary table 3.
- Risk assessment components addressed: entry/release, exposure, consequences.

In the entry assessment, the risk assessor evaluates the pathways through which a pathogen can be moved from the exporting country to the border of the importing country and assesses the likelihood of this occurring. Following the entry of the pathogen into the importing country, the exposure assessment consists of describing the biological pathway(s) necessary for exposure of susceptible animals in the

importing country to the hazards. Establishment is the perpetuation for the foreseeable future of a disease within an area after entry. Spread risk assessment evaluates the likelihood of a pathogen spreading within the imported country. Finally, consequence assessment consists of describing the relationship between specified exposures to a biological agent and the consequences of those exposures [22].

Table 1
Search string used in the present study

#1	**Keywords**
	pathogen* OR disease* OR infectious OR zoonotic OR zoonoses OR emerging OR microorganism* OR virus* OR foodborne OR transboundary OR "animal disease*" OR "food safety"
#2	"risk assessment" OR "risk analysis" OR "risk " OR "likelihood" OR "assessment*"
#3	import*" OR "introduction" OR "importation" OR "entry" OR "border control" OR "cross-border"
#4	"Formal Trade" OR "Regulated Trade" OR "Legal Trade" OR "Informal Trade" OR "Unregulated Trade" OR "Illicit Trade" OR "Smuggling" OR "Black Market" OR "illegal Trade" OR trade*
#5	Animal product*" OR "product* of animal origin" OR "meat" OR "dairy" OR "eggs" OR "honey" OR "seafood" OR "milk" OR "offal*" OR "raw meat" OR "bushmeat" OR "bone*" OR "animal origin*" OR "livestock product*
#6	#1 AND #2 AND #3 AND #4 AND #5

Table 2
Inclusion and exclusion criteria used to evaluate the eligibility of the studies

Criteria	Inclusion	Exclusion
Study criteria	Studies assessing disease risks associated with POAO (meat, dairy, seafood, eggs, honey, etc.) by formal, informal, or mixed trade.	Studies focused solely on live animals, plants or POAO not destined for human consumption (i.e., feathers, hides, semen, etc.).
RA methods and type	Qualitative or quantitative estimates of risk of disease entry, exposure, consequence or establishment	Studies conduct comparisons between different RA methodologies.
Hazard	Animal and zoonotic pathogens (bacterial, viral, parasitic)	Chemical Risk Assessment (RA)
Study Types	Risk assessment reports, Peer-reviewed articles, grey literature (governmental risk assessments)	Surveillance studies, prevalence studies without risk modelling, opinion articles, and studies unrelated to risk assessment in POAO importation (e.g., domestic trade, review of the available data, or general food safety).
Language	No restriction	-
Timeframe	No restriction	-

Results

Search results

A total of 2,541 records were initially identified. After removing 841 duplicates, 1,700 records were screened for title and abstract. During the first screening stage, 1,509 records were excluded based on the exclusion criteria. An additional 159 records were excluded after full-text screening (Fig. 1).

Finally, 50 records met the inclusion criteria and were included in the present study, including eligible records that were added from the reference (n = 7) and grey literature (n = 11). The study by Morley (1993) [23] investigated different pathogens across distinct commodities and was considered as two separate studies. Consequently, a total of 51 studies were included in this review.

Study Characteristic

The search strategy included articles published over the past three decades (1993–2025). Research activity remained relatively low until the early 2000s (n = 11) but increased thereafter, reaching a total of 40 studies in the subsequent years. Most of the included studies applied risk assessment approaches consistent with the framework recommended by the World Organisation for Animal Health (WOAH, previously OIE) [24], which typically includes the following steps of hazard identification, entry

assessment, exposure assessment, consequence assessment, and overall risk estimation. Only one study followed the Biosecurity Import Risk Analysis Guidelines of Australia [25, 26].

Within the included RA, different analytical approaches were applied depending on the availability of data and the objectives of the study, such as qualitative, semi-quantitative or quantitative approaches. Out of the 51 studies included in this review, 39.2% (n = 20) applied a qualitative approach, 15.7% (n = 8) used semi-quantitative methods, and 45.1% (n = 23) conducted quantitative analysis (comprising 2 deterministic and 21 probabilistic models) (Fig. 2). The main difference between these methods is how they estimate the risk. Qualitative assessments use descriptive likelihood categories (such as negligible, low, moderate, and high), semi-quantitative studies utilise scoring or ranking systems, and quantitative analyses apply mathematical models to calculate the likelihood of disease introduction.

Some of these studies also incorporated additional analytical tools within these broader methodological categories to evaluate the likelihood of disease incursion. For example, East et al. (2013) used Multi-Criteria Decision Analysis (MCDA) to rank disease risks. Other studies utilised disease monitoring or early warning systems, including the International Disease Monitoring Plus (IDM+) and the IDM “Risk of Incursion” models, which are intended to facilitate surveillance and early identification of emerging disease threats [27, 28]. In addition, Costard et al. (2013) [29] relied on proxy indicators such as trade volumes, geographical data, commodity data or the number of travellers from affected regions to approximate the likelihood of pathogen introduction when detailed data were unavailable.

The included studies had a range of different objectives, including supporting risk-based surveillance (20 studies, 39.2%), informing policy decisions (12 studies, 23.5%), providing frameworks for rapid emergency preparedness and response to outbreaks (11 studies, 21.6%), and supporting border control activities (8 studies, 15.6%).

The geographical distribution of the included studies was defined based on the importing countries assessed (the countries for which the risk of pathogen introduction was evaluated) (Fig. 3). The United Kingdom was the most frequently assessed importing country (n = 8), followed by New Zealand (n = 4), China (n = 3), Australia (n = 3), and the United States (n = 3). In addition to national-level assessments, several studies evaluated broader geographical scales. Seven studies evaluated broader regional perspectives, including all European Union Member States, while worldwide assessments were conducted in two studies. Four studies did not specify a geographical focus.

The distribution of risk assessment components varied significantly across the included studies, with most of the studies focusing primarily on the early stage of the risk pathway, particularly the likelihood of pathogen entry into the importing country. Out of 51 studies, 23 studies (45%) focused exclusively on entry assessment. The remaining 28 (55%) studies evaluated the entry together with one or more additional components of the risk pathway, most commonly exposure assessment in 19 studies, which examines the probability that susceptible animals come into contact with the pathogen after entry. In contrast, fewer studies (n = 8) focused on the later stages of the pathway, such as establishment, spread, consequence assessment, or risk management measures after pathogen introduction. Moreover,

one study assessed exposure and consequence only, without evaluating entry. This study was retained because it evaluated the risk associated with imported POAO after introduction into the importing country and therefore remained relevant to the objectives of this review (Fig. 4).

When stratified by an analytical approach, qualitative models showed the greatest diversity in component coverage, covering entry alone or combining exposure, consequence, and management. In contrast, quantitative and semi-quantitative approaches were more frequently limited to entry only or entry with exposure assessments (Fig. 4).

Among the pathogens assessed across the included studies, ASFV was the most frequently assessed pathogen, appearing in 19 studies out of 51 (37.2%), followed by FMDV (n = 17, 33.3%). Both pathogens were frequently analysed within frameworks focusing on the early stage of the risk pathway, particularly entry only or in combination with exposure and consequences. Methodologically, both ASFV and FMDV were assessed mostly quantitatively (10 studies for each), whereas qualitatively (5 studies for each) and semi-quantitatively studies were applied less frequently (four studies for ASFV and two for FMDV). Classical swine fever virus (CSFV) was evaluated in 8 studies (15.7%) focusing on entry only or combined with exposure, establishment, and spread, utilizing quantitative-probabilistic (n = 4 studies), quantitative-deterministic (n = 1 study), and semi-quantitative (n = 3 studies) approaches. Additionally, swine vesicular disease virus (SVDV) and porcine reproductive and respiratory syndrome virus (PRRSV) were assessed in three (5.9%) and two (3.9%) studies respectively. Notably, other zoonotic pathogens were assessed mainly for entry combined with exposure or consequence assessment, such as *Trichinella* spp. (n = 4, 7.8%), Bovine spongiform encephalopathy (BSE) prions (n = 3, 5.9%), highly pathogenic avian influenza virus (HPAIV) (n = 2, 3.9%), Hendra virus (HeV) (n = 2, 3.9%), and Nipah virus (NiV) (n = 2, 3.9%). Moreover, a wide variety of pathogens (n = 62 pathogens) such as; *Brucella abortus*, *Mycobacterium bovis*, *Coxiella burnetii*, bovine leukaemia virus (BLV), lumpy skin disease virus (LSDV), Ebola virus (EBOV), HeV), Marburg virus (MARV), Middle East respiratory syndrome coronavirus (MERS-CoV), African horse sickness virus (AHSV), Aujeszky's disease virus (ADV), Capripoxvirus (CaPV), peste des petits ruminants virus (PPRV), and bluetongue virus (BTV) were assessed once across 12 studies (23.6%) (Fig. 5).

Regarding the type of trade pathways assessed, the majority of the risk assessments involved formal trade, either exclusively or in combination with informal pathways (n = 42, 82.3%). Specifically, 22 studies (43.1%) focused exclusively on formal trade, while only 9 studies (17.6%) assessed informal trade alone. The remaining 20 studies (39.2%) evaluated both pathways simultaneously. More in-depth, formal trade pathways were most often reported in broad or unspecified terms, with limited differentiation between specific routes. In contrast, informal trade was primarily linked to passenger-mediated routes through smuggled POAO via air freight, sea, or land border. Other informal pathways, such as postal consignments and courier shipments, were only rarely considered, indicating that these routes remain underrepresented in the current risk assessment literature.

Most RAs assessed more than one commodity; therefore, the number of studies reported for each commodity exceeds the total number of included studies (n = 51). Overall, RAs showed a strong focus on meat and meat products, which were evaluated in 72.5% (n = 37) studies, highlighting their important role in the potential introduction of TADs. These studies primarily addressed the commodities derived from pigs and bovines with different trade types, either formal (n = 17) or informal (n = 9), and combined formal–informal pathways (n = 11). The pathogens most frequently investigated in relation to meat products were ASFV, FMDV and CSFV (Fig. 6).

Milk and dairy products represented the second most frequently examined category, although they are less studied than meat, appearing in 9 (17.6%) studies. Of these, six studies focused on formal trade and three considered mixed formal and informal trade. Compared with meat, dairy-related assessments covered a broader diversity of pathogens, with FMDV being the most assessed (n = 4 studies). Other pathogens were evaluated only one time, including *Brucella abortus*, *Mycobacterium bovis*, *Coxiella burnetii*, LSD virus (LSDV), Middle East respiratory syndrome coronavirus (MERS-CoV), Capripoxvirus (CaPV), peste des petits ruminants virus (PPRV), Bovine leukemia virus (BLV) and bluetongue virus (BTV). Furthermore, bush meat was assessed in 3 (5.9%) studies mainly for the likelihood of entry and exposure of NiV, EBOV; HeV; MARV; MERS-CoV and *Hypoderma bovis*. One study examined formally imported fish products and provided a detailed evaluation of entry, exposure, and consequence of tilapia lake virus. Additionally, poultry meat and by-products were assessed in three studies for viruses and bacteria such as HPAIV, avian paramyxovirus, fowl adenoviruses, Marek's disease virus, avian hepatitis E virus, avian enterovirus-like viruses, arboviruses, astroviruses and avian adenovirus, splenomegaly virus, *Bordetella avium*, *Mycoplasma* spp., *Ureaplasm*a spp., *Ornithobacterium rhinotracheale*, *Riemerella anatipestifer*, and *Salmonella arizona*, *Leucocytozoon* spp., *Planococcus* spp., *Brachyspira* spp. and *Borrelia* spp. Unspecified products of multiple species were assessed in 5 studies (9.8%) for several pathogens with the most common are ASFV, FMDV and SVDV (Fig. 6).

Data sources used to parameterise the risk assessments varied across studies. Prevalence data, which are essential for estimating the likelihood of pathogen presence in the exporting population, were mostly obtained from the WOAH–WAHIS database (66.7%, 34/51 studies). A smaller proportion of studies 8% (n = 4) relied on multiple data sources, such as National Animal Health and Agrifood Quality Service (SENASA), AVIS [30], USDA [31], EMPRES [32], EUFMD [33], laboratory test results, and reports or documents from authorized agencies. Two studies (3.9%) used prevalence estimates derived from scientific literature, and one study (2%) utilized the RASFF trade monitoring and alert system [34]. Notably, 10 studies (20%) did not clearly report the source of prevalence data. Trade data used to characterise the volume and frequency of commodity movements were primarily derived from official databases such as Trade Control and Expert System in the EU (TRACES) [35], and Comext-Eurostat [2]. Additionally, parameters related to pathogen survival, inactivation, and dose–response relationships were obtained from scientific literature (Supplementary Material – Table 5).

Discussion

This systematic review provides a comprehensive overview of the various approaches used to assess import risks associated with the introduction of animal diseases through both formal and informal trade of POAO intended for human consumption. The movement of food commodities represents a well-recognised vehicle for the transmission of TADs, especially when pathogens can persist in them and enter new territories through trade or human-mediated transport. For that, IRAs have an important role in supporting risk managers to identify and prioritise relevant introduction pathways and design appropriate mitigation measures [2]. Overall, our results showed diversity among the included studies in terms of methodology, the risk assessment components covered, commodities and pathogens assessed, trade pathways evaluated, and data sources used.

The number of IRA studies has increased over time, with a marked rise in recent years (Fig. 2). This trend probably reflects the growing awareness of the risk associated with the globalisation of trade and the increasing occurrence of TADs outbreaks. In particular, the spread of ASFV across Europe since the first incursion into the EU in 2014, followed by its expansion into Asia in 2018 appears to have been a major driver of research activity [6], as evidenced by the higher number of studies focusing on this pathogen during this period. A similar pattern was observed for FMDV studies, which RAs studies remains constant during this period due to its high transmissibility and significant economic impact [1, 2]. However, this temporal increase should be interpreted with caution due to the fact that veterinary IRAs were mostly performed after the implementation of the WTO Sanitary and Phytosanitary (SPS) Agreement in 1995 [7]. Overall, these patterns suggest that IRA studies are often conducted in response to evolving epidemiological situations in exporting countries, with importing countries seeking to evaluate and manage the risk of disease introduction through both formal and informal pathways.

The methodological approaches used in this review varied from qualitative to semi-quantitative and fully quantitative methods, indicating differences in data availability, study objectives, time and resources available to conduct the assessments, available budget, technical capacity, and analytical expertise. Although quantitative approaches accounted for 45.1% of studies, with probabilistic models being the most commonly applied, qualitative methods remained widely used (39.2%). This may be attributable to the lack of the data required to fully parameterise quantitative models, especially when assessing poorly understood or inadequately documented pathways, such as informal trade. Qualitative methods are more flexible, making them suitable in cases of limited data and more valuable for generating timely insights and facilitating a broad conceptual understanding of risk. On the other hand, qualitative methods may be more subjective and less reproducible compared to quantitative models [17]. This variability may affect the comparability and consistency of risk estimates across studies, highlighting the need for greater standardisation of methodological approaches and improved data availability and quality to support more robust and transparent risk assessments [36]. Moreover, the study also suggests the need for better incorporation of uncertainty and variability, clearer identification of uncertainty sources, and more consistent use of sensitivity analyses. Semi-quantitative approaches seem to be in between both, enabling a more structured comparison of risks through scoring or ranking systems while avoiding the data demands of fully quantitative models [37]. It is noteworthy that, while quantitative and semi-quantitative approaches provide a numerical risk estimate, there is no clear advantage of these

approaches over qualitative methods and caution is advised when interpreting these outputs, as they may provide a misleading impression of precision and objectivity [37].

Many IRAs focus primarily on estimating the probability of pathogen entry, while comparatively fewer assess the probability of a first infection occurring following exposure of susceptible animal populations. This disparity likely reflects the greater methodological complexity associated with modelling exposure pathways. Whereas entry probabilities can often be estimated using trade volumes, disease prevalence, and commodity-specific pathogen survival data, the exposure phase requires the representation of multiple behavioural and environmental processes that are often difficult to simulate and parameterise. These include, for example, swill feeding practices, improper disposal of contaminated food waste, landfill access by wildlife, and indirect contacts between contaminated products and susceptible animals [38, 39]. Consequently, exposure assessments often involve a larger number of assumptions, higher uncertainty, and substantial data gaps. Furthermore, the probability of exposure is considered very low in countries and regions where swill feeding is prohibited or strictly regulated, as this practice represents one of the most important pathways through which pathogens present in contaminated animal products can reach susceptible livestock populations. For example, in the European Union, the ban on swill feeding was implemented following the 2001 foot-and-mouth disease outbreak in the United Kingdom and remains a key mitigation measure against the transmission of food-borne animal pathogens. As a consequence, the processes leading to pathogen exposure are often difficult to characterise and model, as they depend on a series of infrequent and poorly documented events. This may explain why many studies stopped at the entry assessment stage.

In total, the IRA of POAO addressed 72 pathogens, with ASFV (37.2%) and FMDV (33.3%) being the most studied pathogens, with a focus on the entry stage often in combination with exposure. These findings are in agreement with a recent literature review focused on live animals where FMDV and ASFV were the predominant pathogens assessed quantitatively [16]. This predominance is likely attributable to the current geographical distribution of the disease and the epidemiological characteristics of ASFV, particularly its environmental stability and persistence in pork and pork products. The virus can survive for extended periods, from several months in chilled meat, to more than two years in frozen meat, making contaminated food a relevant pathway for ASF introduction into disease-free areas [11, 40]. In addition, the number of RAs increased following the geographic expansion of the disease, with ASF being one of the most significant examples of transboundary threats to the swine industry for which no vaccine is available [36–39]. Since its introduction in Georgia in 2007 [41], the virus has spread throughout Eastern Europe and the Caucasus region, and it continues to circulate in domestic pigs and wild boar populations in countries such as Russia, Armenia, Azerbaijan, Ukraine, Belarus, Lithuania, and Poland [40–42]. More recently, sporadic outbreaks have been reported in the wild boar populations of Western Europe (Belgium, Germany, Italy, Spain), posing a threat to the European pig industry as a whole. Furthermore, in 2021 ASFV was also reported in the Dominican Republic highlighting the continued risk of long-distance spread [42, 43].

FMD was the second most assessed pathogen across our review. This situation may be due to the high transmissibility of FMDV and its broad host range across multiple livestock species [2]. Moreover, outbreaks in a trading partner or neighbouring country attract more interest, funding, and risk assessment reports, as seen with recent FMD outbreaks in Europe [44]. These pathogens have more studies compared to the other pathogens because of their huge economic loss. For example, after FMDV outbreak in Taiwan, the estimated cost was $379 million due to the slaughter of around 40% of the swine population in the country (more than 4 million pigs) [45, 46]. In addition, the trade ban on pork to Japan resulted in a financial loss of $1.6 billion [46]. Moreover, the 2001 outbreak of FMD in the UK had a total impact of $11.9-$18.4 billion [47]. Also, The potential introduction of ASFV to the USA is estimated to cost $16.5 billion during the first year of the outbreak [48].

CSFV was less frequently studied [1, 44–48], with assessments mainly focused on entry and exposure. Nevertheless, the disease remains an important concern because of its economic impact, as experienced in the 1997–1998 outbreak in the Netherlands, which resulted in the depopulation of 1.1 million piglets from 1,300 farms and required slaughter of 700,000 pigs across 429 infected farms [49].

Fewer studies addressed the remaining pathogens. This likely reflects their limited global impact compared with ASFV and FMDV, which has attracted less attention from risk assessors. For example, hazards relevant to human health through meat consumption were assessed mainly for *Trichinella* spp. [23, 46–48] and BSE prions [23, 50]. However, the limited representation of other pathogens is not necessarily lower research interest, it likely reflects that these pathogens are predominantly transmitted through routes other than POAO intended for human consumption, including live animal movements, vector-borne transmission direct contact. For instance, pathogens like NiV and hepatitis E virus are commonly transmitted through wildlife reservoirs or direct animal contact, with their commodities being less represented in the trade market and therefore limiting its representation in POAO-focused risk assessments The same was observed for HPAIV and PRRSV, with only two studies evaluating the risk of these pathogens via POAOs [46–49] despite their epidemiological and economic importance in the poultry and swine industry [51, 52]. Moreover, introduction of LSDV through meat and meat products was evaluated only in one study [53]. This can be explained because the virus is primarily translocated through non-edible commodities like hides. Similarly, *Hypodermis bovis* was assessed for it is entry and exposure through legal importation of deer game meat once where the commodity serves as a potential vehicle for larval translocation [54].

Meat and meat products were the most frequently POAO studied, highlighting their important role in the introduction of TADs and their association with high-impact livestock disease introduction. For example, products from pigs and cattle such as frozen deboned meat, pig salted or cured meat, bone-in beef and offal are linked to pathogens such as ASFV, FMD and CSFV [55, 56]. In contrast, milk and dairy products are less frequently evaluated, despite their widespread human consumption and their relevance in animal production systems. This may be explained by the effect of processing such as pasteurization, which can reduce pathogen survival. Furthermore, dairy products require specific storage and transport

conditions, making them less likely to be transported through informal or small-scale pathways compared to meat [57, 58]. Other commodities, such as fish products, were assessed for legal entry and exposure of tilapia lake virus in one study [58]. This could be explained by importation of fish products usually in processed format (i.e. canned) that do not typically pose a risk or have lower chances of onward disease transmission and exposure to other fishes and therefore lower risk perception than meat. The number of IRAs for bush meat was limited despite its frequent illegal importation and might be related to a lack of comprehensive data, and the inherent difficulty of tracing its origins. However, their inclusion highlights risks linked to informal trade and wildlife-associated pathogens [59]. This suggests that more RAs are required to understand the risk of disease introduction through these commodities [60].

When looking at trade pathways, a clear imbalance was seen between formal and informal routes, with the majority of studies focused on formal trade alone or in combination with informal. This is due to the availability of data: formal trade is relatively well documented, while informal or illegal trade is more difficult to assess and, therefore, less frequently included in RAs. Within the informal trade pathways, the passenger-mediated route was studied the most, particularly air passengers from outside EU and sea passengers (ferries) [56–60]. This pathway is widely recognised as a high-risk route for disease introduction, of special concern when it involves pathogens capable of surviving in processed or untreated products. Other informal pathways, such as postal consignments or courier shipments, were rarely studied [61]. Moreover, controlling land borders and monitoring the movement of products carried by travellers can be particularly challenging in regions where people and goods can move freely across national boundaries such as the European Union. Similarly, data on products transported by air passengers travelling within such free-movement areas are often unavailable. This situation likely reflects both data limitations and methodological challenges, rather than a lack of importance, and suggests that their contribution to disease risk may currently be underestimated.

Taken together, these findings highlight a gap identified across the assessment of the informal trade of POAO, although it is widely recognised as a potential source for disease introduction, which is not fully represented in the current studies due to the lack of data in comparison to formal trade. Addressing this gap will require more targeted data collection efforts. In particular, dedicated studies should be conducted at the national level to better characterise informal movements, including (i) the frequency of informal import of POAO, (ii) the type of products involved, including not only the commodity category but also the level of processing or treatment, and (iii) the geographical origin of these products. Such information would provide a more realistic basis for parameterising risk assessments and improving the representation of informal pathways in these studies. Another important gap is the lack of information on pathogen characteristics, particularly at the strain level, and most studies address pathogens at a general level, without taking into consideration differences in virulence, environmental resistance, or survival capacity between strains. This may limit the ability of risk assessments to appropriately reflect the actual situation.

Despite these gaps, the included studies demonstrate some strengths. Most followed internationally recognised frameworks and made use of available data sources, ensuring consistency across assessments. At the same time, several limitations remain, as many studies depend on a limited set of data sources, particularly international disease reporting systems and official trade databases, which primarily capture formal trade. Addressing the identified data gaps will require more systematic data collection, especially at the border entry point. Specific survey and monitoring activities should be applied to better characterise informal trade, including the frequency and origin of these commodities. Such information is essential to better estimate the likelihood of pathogen introduction and its pathway. Conducting QRA studies is highly resource-intensive, requiring robust data, specialized scientific expertise, significant time, and adequate funding. These demands often limit their feasibility in low-resource settings. Consequently, this limitation may partly account for the geographic imbalance observed in published QRA assessments, the majority of which originate from higher-income countries. As a result, international collaboration across nations of all income levels is crucial to addressing global disease risk [62].

This review highlights the important role of IRA in evaluating the introduction of TADs through the trade of POAO. The findings show that current approaches are focused on high-impact pathogens, especially those associated with meat products and that formal trade is better represented compared to informal trade. Future efforts should focus on improving data availability and traceability, especially for informal trade and non-commercial trade pathways, as well as strengthening international cooperation and the integration of multiple sectors, such as veterinary, public health, wildlife, and trade sectors to support more effective surveillance and control systems. In addition, expanding attention to underrepresented commodities, such as dairy products, aquatic animal products, poultry products, and wildlife-derived products (bush meat), may further support more comprehensive risk characterisation and a solid basis for decision-making in an increasingly interconnected global trade environment.

Declarations

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Author Contribution

RC conceived and coordinated the study. AAKZ and RC performed the literature search, screening, eligibility assessment, and study selection. AAKZ extracted and analysed the data and prepared the first draft of the manuscript. RC supervised all stages of the study, contributed to data interpretation, and

oversaw the preparation and revision of the manuscript. GB, BC, LCGV, and CJDV contributed to the interpretation of the findings and critically reviewed the manuscript. All authors contributed to the development of the final manuscript, reviewed its content, and approved the final version.

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Figures

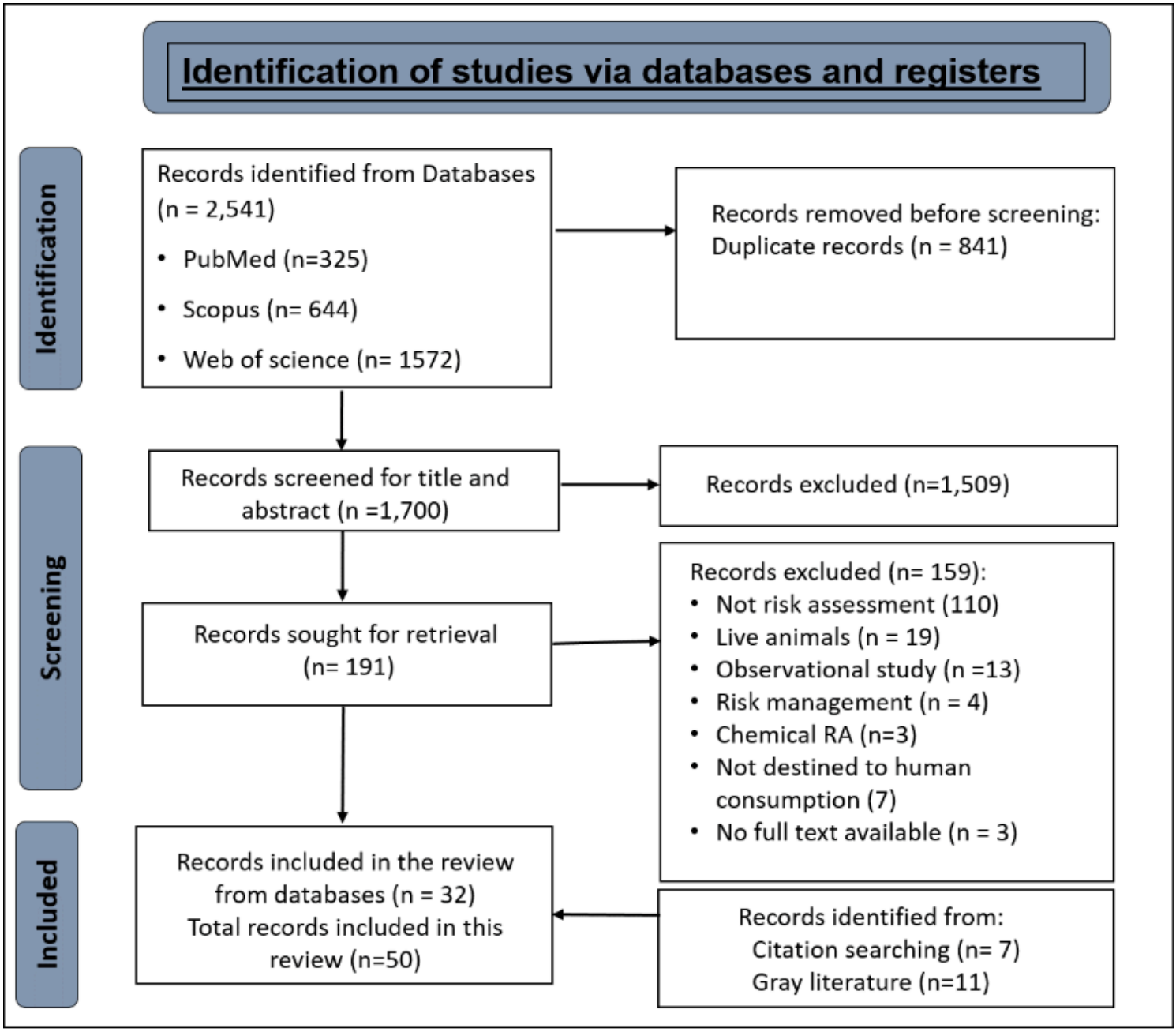


Figure 1

Flow chart representing the search strategy and selection of articles according to Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)

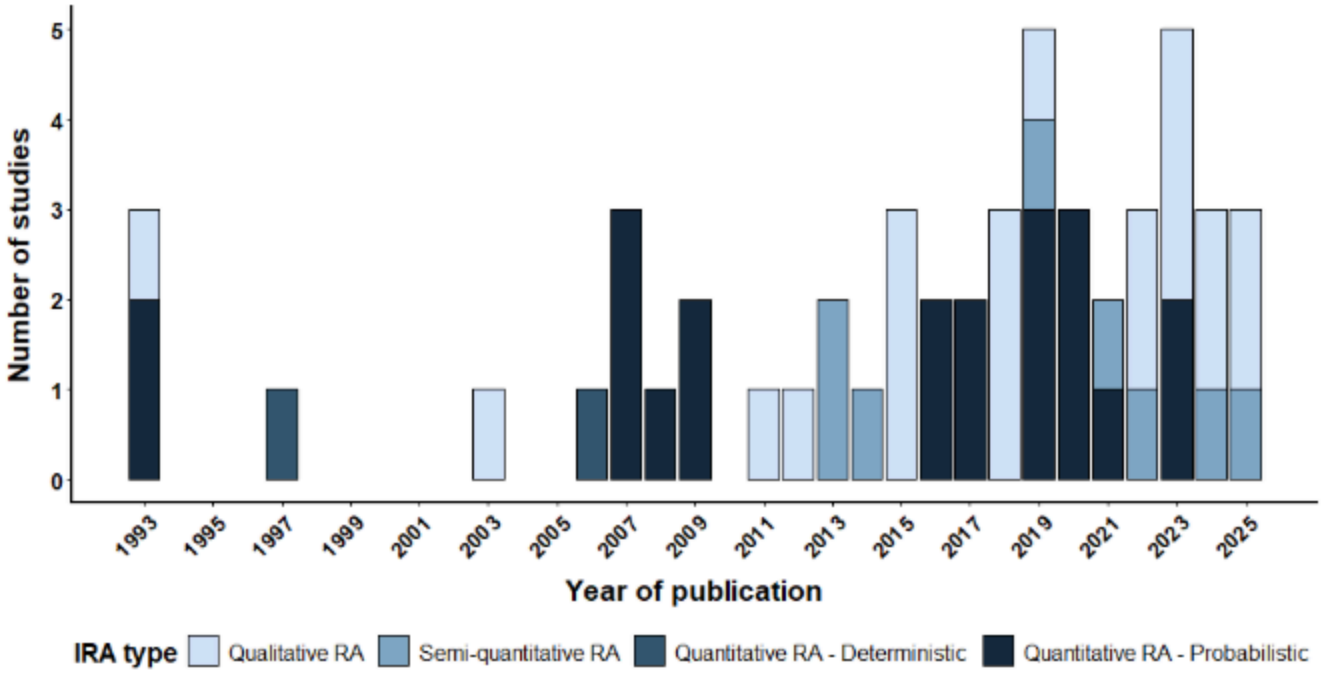


Figure 2

Number and type of import risk assessment (IRA) studies for products of animal origin across 1993 - 2025. RA = Risk assessment

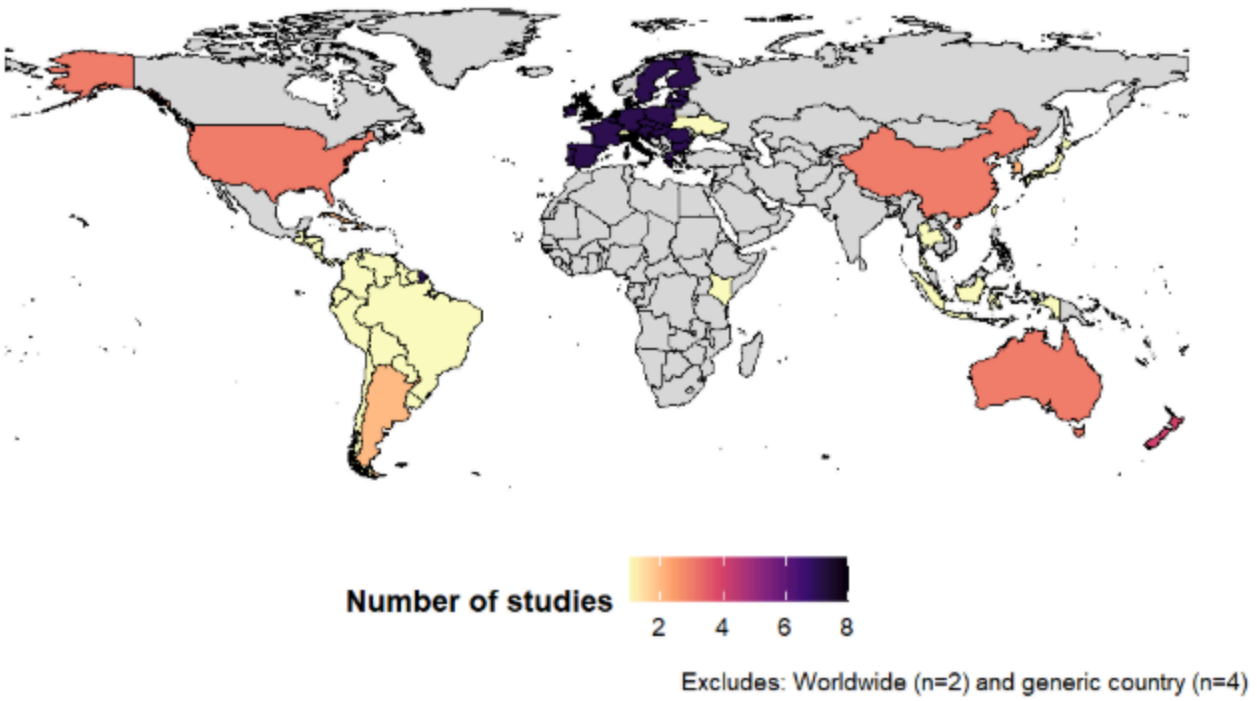


Figure 3

Geographical distribution of risk assessments. Regional studies (e.g., EU, Americas, and the Caribbean) are grouped under a single colour. For individual countries, totals include both country-specific studies and those conducted at the regional level (e.g., Italy: 1 national study plus 7 EU studies; total = 8).

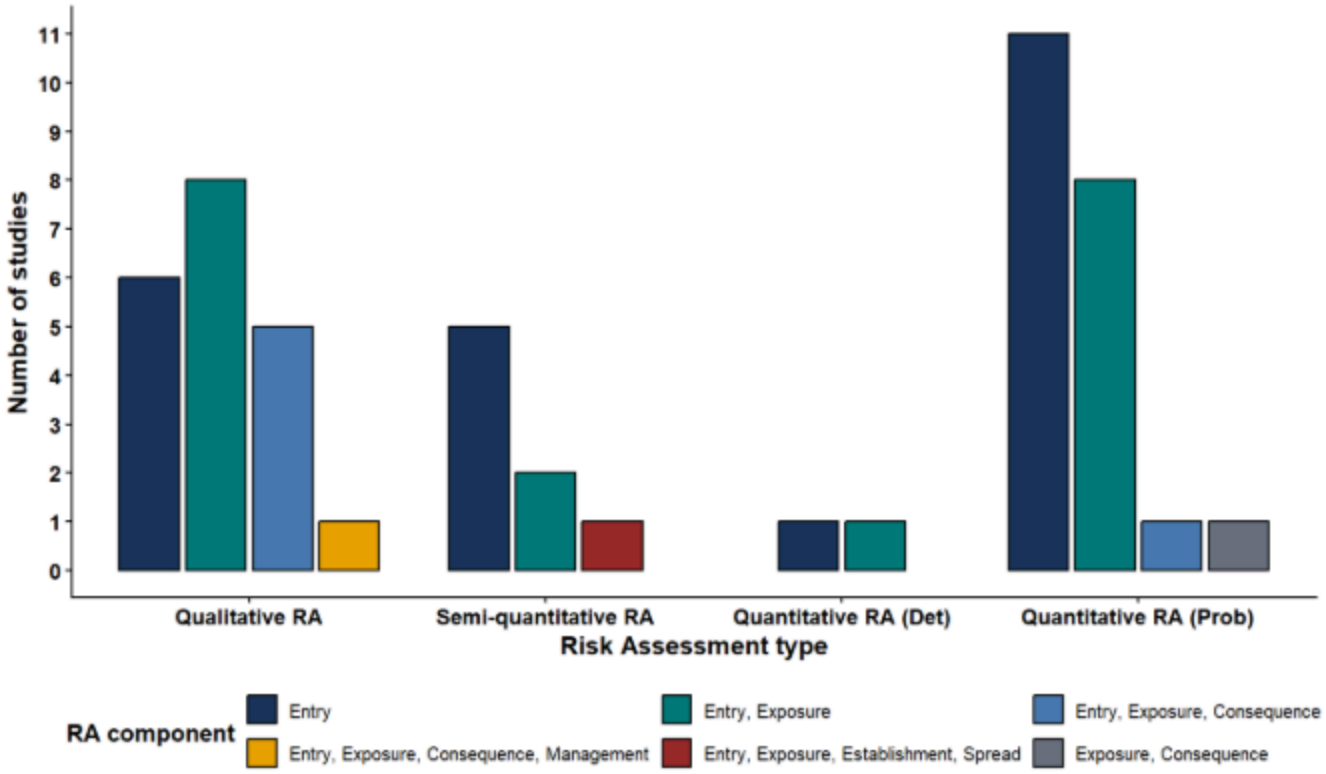


Figure 4

Distribution of risk assessment types and their associated components across the reviewed studies. Quantitative denote probabilistic (Prob=Probabilistic) and deterministic (Det=Deterministic) approaches, respectively.

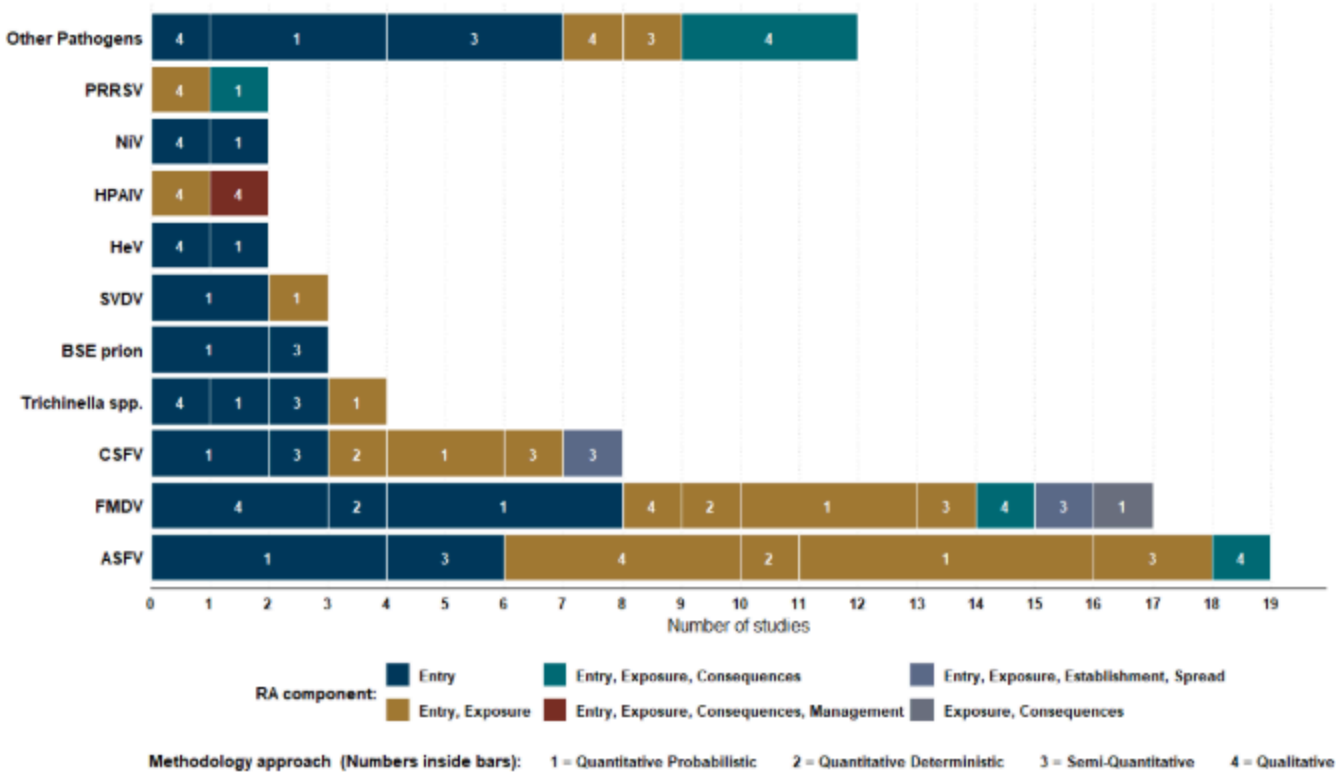


Figure 5

Risk Assessment studies and the components conducted for the pathogen. Darker bars indicate Quantitative; faded bars indicate Qualitative. “Other pathogens" includeall the pathogens that were assessed only once.

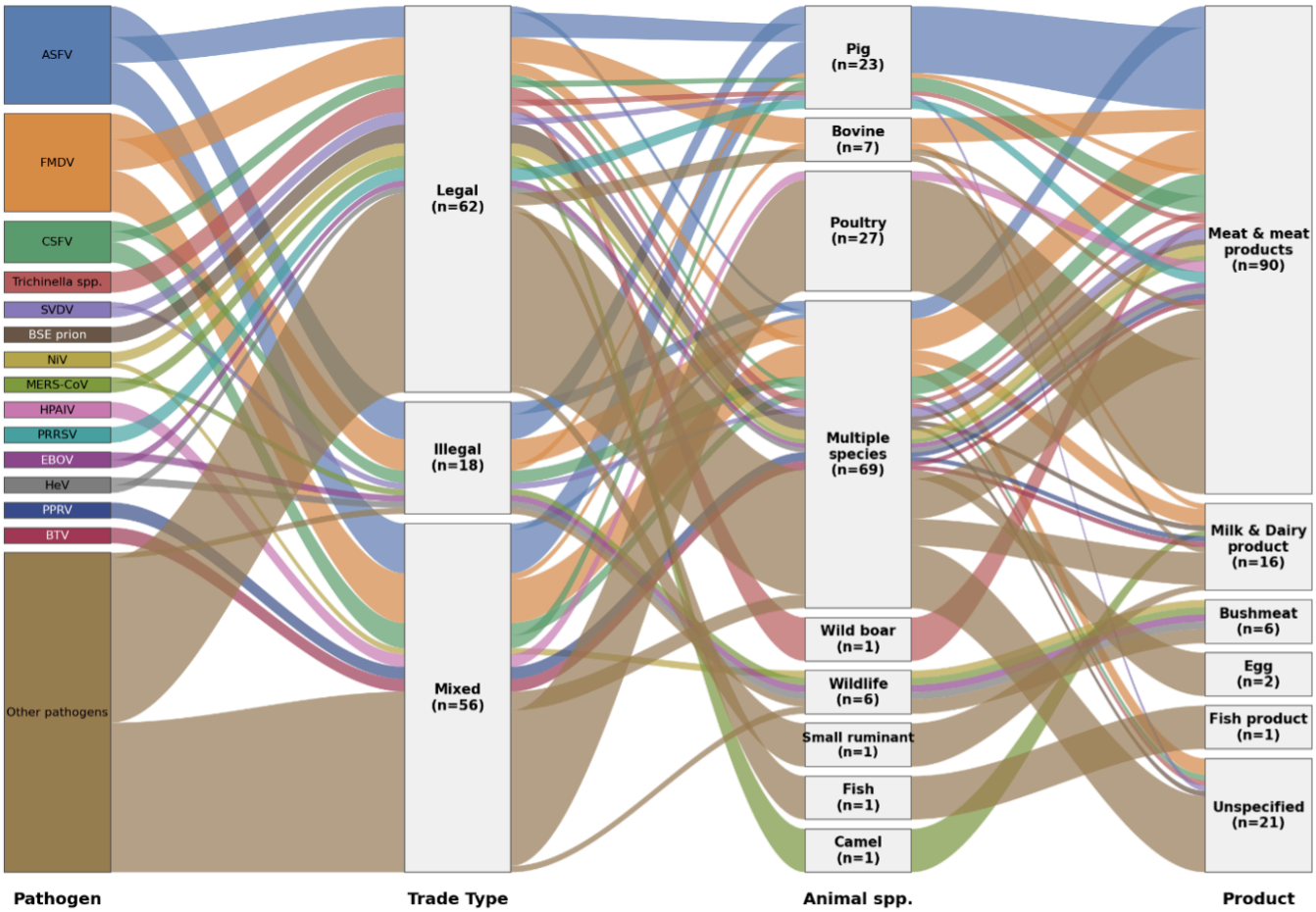


Figure 6

Sankey diagram representing the risk assessment distribution per (i) pathogen, (ii) trade type, (iii) animal species, and (iv) type of animal product. ASFV = African swine fever virus; FMDV = Foot-and-mouth disease virus; CSFV = Classical swine fever virus; SVDV = Swine vesicular disease virus; BSE prion = Bovine spongiform encephalopathy prion; NiV = Nipah virus; MERS-CoV = Middle East respiratory syndrome coronavirus; HPAIV = Highly pathogenic avian influenza virus; PRRSV = Porcine reproductive and respiratory syndrome virus; EBOV = Ebola virus (Zaire ebolavirus); HeV = Hendra virus; PPRV = Peste des petits ruminants virus; BTV = Bluetongue virus; POAO = products of animal origin. "Other pathogens" includes pathogens that were assessed only once. Note that the number of combinations shown here exceeds the number of included studies (n = 51) because some of the included studies assessed more than one pathogen, trade type, POAO or animal species.

Supplementary Files

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