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Economic evidence for the control of meatborne parasites in Europe: A scoping review

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ABSTRACT

Meatborne parasites pose significant public health concerns and lead to substantial economic losses. Decisions regarding the introduction of risk-based control strategies to manage these parasites depend on the availability of robust and comparable economic data. To understand the current economic evidence available on meatborne parasite control, a scoping study was conducted to provide recommendations on optimal investment. This study is a part of the COST Action CA18105 (Risk-based Meat Inspection and Integrated Meat Safety Assurance [RIBMINS]), which supports the development and implementation of risk-based meat inspection programs across the EU and partner countries. This study synthesized available evidence published between January 1, 1980, and April 1, 2022, on interventions for controlling four meatborne parasites (*Taenia saginata*, *Taenia solium, T. gondii,* and *Trichinella spiralis*) where economic analyses had been conducted in COST Action CA18105-affiliated countries. We considered interventions conducted at any node within meat value chains, including those undertaken by health systems targeting consumers. Twelve relevant articles related to eleven distinct studies were identified. The outcomes of economic analyses were recorded, and a critical appraisal of these studies was carried out. The economic data identified have been summarized narratively, and this scoping review has revealed a scarcity of economic data on which to base decisions regarding meatborne parasite control and a lack of standardization in the approaches used for economic analysis. We recommend consensus building among researchers working in the food safety assurance space to standardize the methods and reporting of economic analysis of interventions, similar to efforts that have been made in the health economics space.

1. Introduction

Foodborne protozoans and helminth parasites can infect humans through the consumption of contaminated food, representing a significant global public health concern by causing human morbidity and mortality. They also have a substantial economic impact due to the condemnation of food products, the time required to implement inspection or treatment protocols, and the cost of illness inflicted upon infected individuals (Devleesschauwer, Bouwknegt, et al., 2017). The disease burden attributable to foodborne parasites (FBPs) has been estimated by the World Health Organization (WHO) Foodborne Disease Epidemiology Reference Group (FERG) to be 6.64 million disability-adjusted life years (DALYs), with a 95% uncertainty interval of 5.61–8.41 million (Torgerson et al., 2015). However, the economic impact of FBPs has been less well quantified, indicating that more robust estimates are needed if these pathogens are to receive the attention they require from decision-makers. Four meatborne parasites of importance in the European context have been selected for the focus of this scoping review: *Taenia solium*, *Taenia saginata*, *Trichinella* spp., and *Toxoplasma gondii*. Whilst *Taenia saginata* and *Trichinella* spp., are only transmitted to humans through the consumption of meat, *Toxoplasma gondii* and *Taenia solium* have meatborne and non-meatborne transmission routes. Whilst *Echinococcus* spp. Are also important foodborne parasites, as human infection is via contamination (of food, water, soil) with the eggs or

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gravid proglottids excreted from the definitive canine host and not directly through consumption of meat of the intermediate host, the parasite was not included within this review.

Humans are the definitive hosts of the zoonotic helminths *T. solium* and *T. saginata*, through the consumption of undercooked pork and beef respectively. Taeniasis is typically causing mild abdominal discomfort, although rare complications can occur (Okello & Thomas, 2017; Torgerson et al., 2019). Humans can also become aberrant intermediate hosts of *T. solium*, through faecal-oral transmission, leading to severe morbidity, including epilepsy, due to parasitic cysts in the central nervous system (neurocysticercosis) (Garcia, Gonzalez, & Gilman, 2020; Okello & Thomas, 2017). While *T. solium* carries the highest global burden among these meatborne parasites, its risk within the European context is small but not negligible (Devleesschauwer, Bouwknegt, et al., 2017; Havelaar et al., 2015a). Notably, Trevisan et al. (2018) highlighted that little is known about the situation of *T. solium* in Eastern Europe, where ongoing transmission may still occur. This uncertainty underscores the need for enhanced investigation and vigilance. Conversely, *T. saginata* is prevalent across Western European countries, with bovine cysticercosis (BCC) imposing a significant economic burden due to the condemnation of infected carcasses (Jansen, Dorny, Trevisan, et al., 2018; Laranjo-González et al., 2017, 2018; Trevisan et al., 2018). However, similar to *T. solium*, data on *T. saginata* in Eastern Europe remain scarce and of poor quality, highlighting crucial knowledge gaps and underscoring the need for improved surveillance efforts in the region (Jansen, Dorny, Trevisan, et al., 2018; Laranjo-González et al., 2017, 2018; Trevisan et al., 2018).

The intermediate stages of *Taenia* spp. Are identifiable by the naked eye, making meat inspection a crucial method of parasite control in the food chain, though its sensitivity is low (Eichenberger, Stephan, & Deplazes, 2011). Taeniasis in humans can be effectively treated with readily available anthelmintics, such as praziquantel (10 mg/kg), niclosamide (2 g/person), or triple-dose albendazole (3 × 400 mg/person) (Okello & Thomas, 2017). The primary risk factor for cattle infection is the contamination of grazing land or drinking water with sewage effluent, highlighting the importance of effective sewage management as a critical control point for this parasite (Marshall et al., 2016; Usee, Kyvsgaard, Nansen, & Henriksen, 1990).

Toxoplasma gondii is the meatborne parasite with the highest human health burden in Europe (Li et al., 2019). *Toxoplasma gondii* is a ubiquitous protozoan parasite capable of infecting most warm-blooded animals, with cats serving as the definitive hosts and significant reservoirs of infection. Humans can become infected through several routes: consumption of undercooked meat infected with tissue cysts, consumption of food or water contaminated with oocysts from cat feces, transplacental transmission from a primary infection in the mother during the first trimester of pregnancy, or via transfusions or transplantations from infected individuals (Stelzer et al., 2019). Evidence indicates that in Europe, 74–77% of all toxoplasmosis cases are foodborne (Li et al., 2019), with a significant portion being meatborne (Belluco, Simonato, Mancin, Pietrobelli, & Ricci, 2018; Li et al., 2019). Estimates suggest that beef is responsible for 25–38%, small ruminants for 9–18%, and pork for 12–13% of cases, though there are significant local variations (for example, in the Netherlands, pork is the source of 50% of cases and beef and lamb 23%) (Almeria & Dubey, 2021; Hoffmann et al., 2017). A systematic review and meta-analysis of studies published between 2000 and 2020 reported that the overall seroprevalence of anti-T. gondii IgG in European populations was 32.1%, with considerable variability between countries. The occurrence of anti-T. gondii IgM (an indicator of recent infection), reported in 64.7% of studies, reached a pooled seroprevalence of 0.6%. Additionally, among the eight main risk factors identified, 'contact with soil,' 'consumption of undercooked beef,' and 'intake of unwashed vegetables' were most significantly associated with infections (Calero-Bernal et al., 2023).

While human infections are generally asymptomatic, congenital toxoplasmosis can result in abortion, stillbirth, and a range of neurological and cognitive disorders in the fetus or newborn, representing a significant health burden (Torgerson & Mastroiacovo, 2013). Infections in immunocompromised individuals, particularly those with HIV/AIDS or undergoing immunosuppressant treatments, can lead to severe consequences, including visual impairment, encephalitis, and death (Lewis, Clifford, & Nsutebu, 2015). *Toxoplasma gondii* infections in livestock can also lead to abortion and congenital disorders, primarily impacting the small ruminant sector (Stelzer et al., 2019). *Toxoplasma gondii* cysts cannot be detected macroscopically during meat inspection, as they are invisible to the naked eye, and regulatory testing in meat animals is generally not deemed practical due to the absence of sensitive, robust, and reproducible detection methods and the high prevalence in meat animals (Kuruca, Belluco, Vieira-Pinto, Antic, & Blagojevic, 2023). Serological tests may be used within a risk-based meat assurance system, targeting high-risk animals according to proposed harmonized epidemiological indicators, although such a system is not yet operational in the EU (Kuruca et al., 2023). While France and Austria conduct routine serological monitoring of pregnant women for the detection and early treatment of congenital toxoplasmosis, dietary and hygiene recommendations for pregnant women remain the cornerstone of public health protection (Wehbe et al., 2022). These recommendations include avoiding raw or undercooked meat, freezing meat to −12 °C for at least three days, washing vegetables, avoiding contact with cat feces by wearing gloves when handling litter trays or gardening, and adhering to general hygiene practices such as hand washing and ensuring clean drinking water (Wehbe et al., 2022). Although there are no international official requirements for *T. gondii* surveillance, congenital toxoplasmosis in humans is notifiable in most European countries. In animals, toxoplasmosis is notifiable in 14 out of 35 countries, with passive surveillance typically focusing only on abortions in small ruminants (van der Giessen et al., 2021).

Trichinellosis in humans is caused by the ingestion of raw or undercooked meat infected with the encysted larval stage of nematode parasites from the genus *Trichinella* spp. *Trichinella* can parasitize many animal species, though human infections are predominantly acquired from pigs, horses, and game meats, including wild boar, deer, moose, and walrus (Diaz, Warren, & Oster, 2020). After ingestion, the larvae mature in the human small intestine; adults mate and release larvae, which encyst in striated muscles. Thus, both the adult and intermediate stages exist within a single host (auto-heteroxeny). Disease is caused by both the migrating and encystment phases, where the host's immune response leads to a variety of clinical manifestations, including acute gastroenteritis, fever, anorexia, dyspnea, pruritus, edema, and occasionally death through subsequent sepsis or thromboembolism (Diaz et al., 2020). The global burden of trichinellosis is estimated at 550 DALYs/year (Havelaar et al., 2015b), with the highest burden per 100, 000 people in Europe (Li et al., 2019). Between 2019 and 2021, 291 cases of trichinellosis were recorded across 12 outbreaks in the EU and cooperating states. The number of cases detected within the EU has decreased over the past decades, likely due to changes in pig production practices in Eastern Europe, with an increase in pigs kept within controlled housing (Pozio, 2019). In the study by Pozio (2019), the findings suggest that the presence of *T. spiralis* is primarily associated with regions known for backyard and free-ranging pig farming. It is also important to note the growing concern among consumers about the welfare of farmed pigs and the increased popularity of free-range pork, which may affect the prevalence of the parasite in these animals and the risk levels for consumers. An effective strategy against this would be to educate these consumers on the importance of thoroughly cooking pork to mitigate the risks associated with consuming undercooked meat from free-range pigs. Domestic pigs reared for human consumption are predominantly infected by *Trichinella* spp. Through the ingestion of infected small rodents, meat scraps, or cannibalism (Diaz et al., 2020). Therefore, control in livestock focuses on biosecurity. Controlled housing ensures that pigs have no access to outdoor facilities, with appropriate bedding, feeding, and waste management, and that rodent control is in place

(Alban et al., 2011). Encysted larvae cannot be seen with the naked eye, so visual meat inspection is not an appropriate control measure. The Commission Implementing Regulation (EU) 2015/1375 (Commission Implementing Regulation, 2015), as amended by the Implementing Regulation (EU) 2021/519 Commission Implementing Regulation 2021/519 of 24 March 2021, 2021, mandates that muscle samples be collected at the slaughterhouse from carcasses of breeding pigs, outdoor pigs, all solipeds, and wild boars destined for human consumption. These samples are then analyzed for *Trichinella* larvae detection using the magnetic stirrer method for pooled sample digestion or any equivalent method. Moreover, human treatment consists of anthelmintics (400 mg of albendazole twice daily for 10–14 days) and appropriate analgesic treatments (Alban et al., 2020).

As indicated above, controlling these meatborne parasites requires disrupting the transmission of the parasite from one host to another or treating the resulting infection in humans. This can be targeted at different stages of the value chain: the farm, the abattoir, processing, or the consumer level. Determining which control strategy to deploy for a particular meatborne parasite depends on the relevant legislation, the acceptability of an intervention to value chain stakeholders, including consumers, the efficacy of the intervention, and its economic efficiency. Economic analysis clarifies where the costs and benefits of different interventions fall and can guide decisions about redistributive actions such as subsidization or taxation. Various frameworks exist through which the economic efficiency of interventions may be assessed, which can be undertaken from the perspectives of private business operators (e.g., farmers or slaughterhouse owners), the health service, or from a societal perspective, accounting for costs and benefits accruing across multiple different actors (Robertson, Torgerson, & van der Giessen, 2018). To enable comparison of the economic efficiency of various interventions or interventions targeting different parasites, standardized economic frameworks that utilize robust methodologies and are reported transparently for reproducibility are essential. Within healthcare technology assessment (HTA), the Second Panel on Cost-Effectiveness in Health and Medicine offers such methodological guidance. Similarly, the Consolidated Health Economic Evaluation Reporting Statement (CHEERS) provides reporting guidelines for these analyses. However, similar guidelines are currently lacking for the food safety sector, highlighting a gap in the standardized reporting and assessment of economic evaluations in this area (Husereau et al., 2022; Sanders et al., 2016).

The COST Action CA18105 (Risk-based Meat Inspection and Integrated Meat Safety Assurance [RIBMINS]), supported by COST (European Cooperation in Science and Technology) through collaborative research efforts, promotes the development and implementation of a risk-based meat safety assurance system across Europe (https://www.cost.eu/actions/CA18105/). The economic efficiency of different meat assurance systems is an essential source of evidence for decision-makers to draw on when considering whether to implement a system. To assess the scope of literature on economic evidence within meatborne parasite control and synthesize the current evidence, we conducted a scoping review on economic evidence regarding interventions to control meatborne parasites within RIBMINS-affiliated countries.

2. Materials and methods

A scoping review protocol was employed, using a modified PICO (Population, Interventions, Context, Outcomes) statement, to assess evidence for interventions targeting meatborne parasites with economic costing, as detailed below.

2.1. Definitions

Population: This review focused on meat-producing animals, high-risk meat products, and at-risk humans in RIBMINS-affiliated countries, as listed at https://ribmins.com/members/ncp/. '*Meat*' is defined as '*all edible parts of farmed and wild mammals and birds*', adapted from the definition provided by Regulation (EC) No. 853/2004 (Regulation, 2004). Accordingly, this review excludes fish and other non-mammalian animals less commonly consumed by humans (e.g., snails, frogs).

Interventions: Any intervention within the value chain, including at the consumer level, designed to reduce human exposure to or impact from *T. gondii*, *T. saginata*, *T. solium*, or *Trichinella* spp. From meat and meat products, implemented in a COST Action CA18105-affiliated country, and accompanied by an economic analysis.

Outcomes: Cost of the program, cost-benefit ratio, net present value (NPV), internal rate of return, gross margin, cost-effectiveness, break-even point, and least-cost option.

Time frame: Manuscripts published between January 1, 1980, and April 1, 2022.

Search strategy: The search was conducted following the PRISMA guidelines for conducting scoping reviews, with a review protocol that includes the full syntax for searches in PUBMED and Google Scholar, as shown in Supplementary Material 1.

2.2. Literature screening and reviewing

The initial search was conducted by one author (LFT), and all results were imported into Rayyan AI, with duplicate records removed. All authors (ND, PI, CM, and LFT) independently reviewed the titles and abstracts for eligibility based on predefined inclusion and exclusion criteria, followed by double-blinded screening of full-text manuscripts. Included were studies on costing, cost minimization analysis, (societal) cost-benefit analysis ([S]CBA), cost-effectiveness/utility analysis, partial budget analysis, and break-even analysis of interventions to control meatborne parasites in COST Action CA18105-affiliated countries. Excluded were studies not based in the eligible countries, those not reporting an intervention strategy, describing an intervention without economic data, basic epidemiological studies, and studies not focusing on meatborne parasites. For this scoping review, no formal quality assessment was used as an eligibility criterion in the screening process.

2.3. Data extraction

The authors agreed on the types of data to be extracted, guided by the CHEERS 2022 checklist (Husereau et al., 2022), due to the absence of consolidated guidelines for reporting economic evaluations in the food safety sector. These variables included the parasite of interest, country of study and baseline prevalence of the parasite, type of economic analysis, perspective, time horizon, discount rates, description of the intervention and comparator, the costs and outcomes included along with their measurement and valuation, the analytical model used, a summary of main results, and influential variables if a sensitivity analysis had been conducted. These data were extracted into a Word document in table format. Additionally, the authors developed a critical appraisal checklist, structured as yes/no questions based on their review of the studies, as per (Kiiza et al., 2023) (Supplementary Material S2).

3. Results

The database search yielded a total of 307 records, of which 303 were retained after duplicates were removed. Upon screening titles and abstracts according to the inclusion and exclusion criteria, 58 records were deemed eligible for retrieval, yet six were unavailable. After reviewing the full texts of 52 manuscripts, 12 articles met the inclusion criteria for the final data extraction (Fig. 1). These 12 articles represent 11 studies, as one paper outlines the methodological framework used in another paper selected for inclusion (Suijkerbuijk et al., 2018, 2019). Only one study was published before 2000. *Toxoplasma gondii* was the most frequently investigated parasite (in 6 out of 11 studies), followed by *T. saginata* (in 4 out of 11 studies). *Trichinella spiralis* and *T. solium* were each the focus of one eligible article. The studies on meatborne

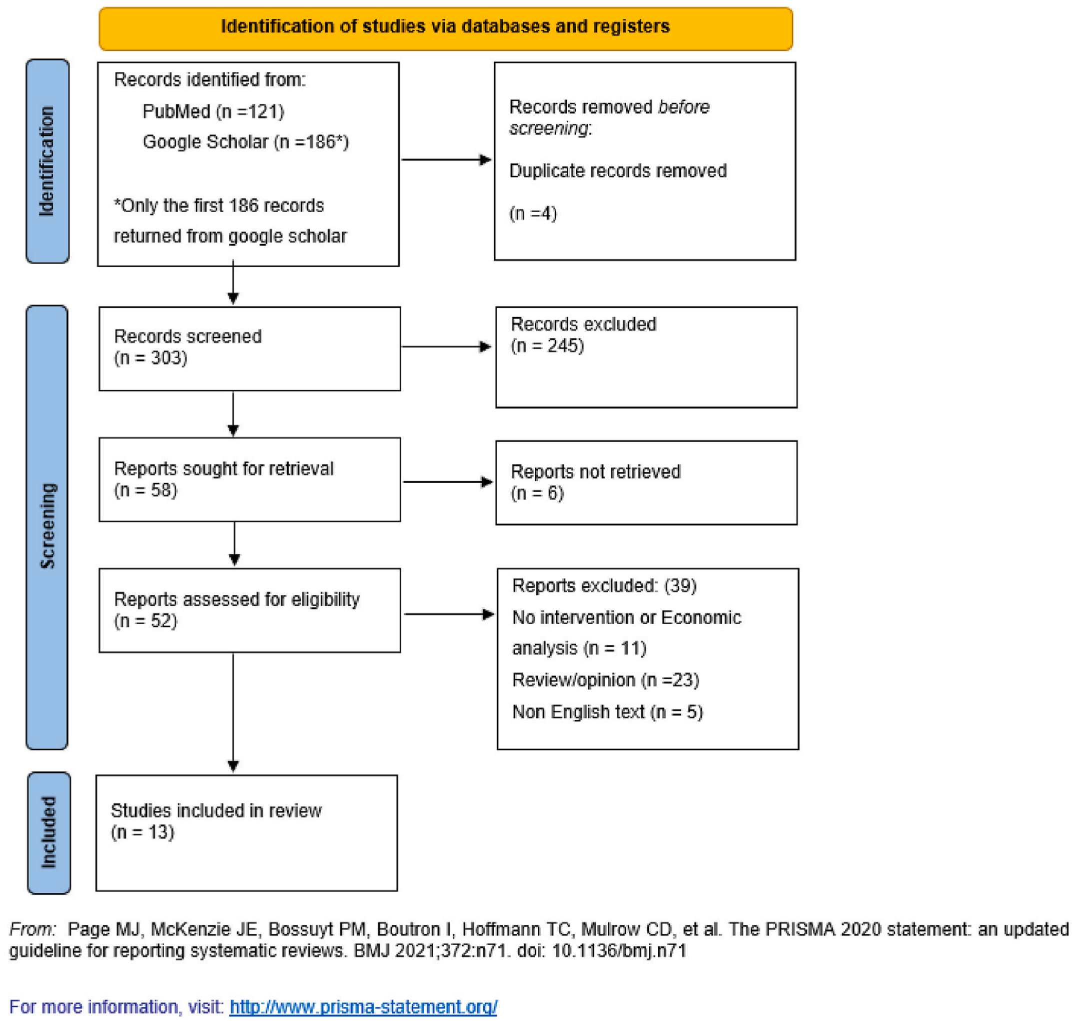

Fig. 1. PRISMA Flow diagram.

parasite control were conducted in Austria (1), Belgium (2), France (1), the Netherlands (3), the UK (2), Spain (1), and Serbia (1).

To provide an overview of the literature, the results of the scoping review are presented in two sections: 1. A general description of the interventions implemented for each parasite genus and the corresponding economic analyses, and 2. A detailed description and critical appraisal of the various economic analyses applied across all three parasitic genera. Data extracted from the identified publications are available in Supplemental Material S3.

3.1. *Intervention strategies against identified meatborne parasites*

3.1.1. *Interventions for Toxoplasma gondii*

In total, six studies on *T. gondii* control were identified. Of these, three studies evaluated consumer-focused interventions for detecting and managing congenital toxoplasmosis, and three assessed interventions related to pig slaughter.

3.1.1.1. Screening for congenital toxoplasmosis. The most common control intervention against congenital toxoplasmosis is prenatal screening to detect and treat active infection in pregnant mothers. Two studies compared prenatal screening with no screening, and one study assessed screening of neonates. The findings of the articles are summarized in Table 1.

The conclusion is that prenatal screening offers clear economic and health benefits compared to either no screening or neonatal screening, and therefore, it should be implemented or continued.

Table 1
Summary of findings on control interventions against congenital toxoplasmosis.

Author and year	Country	Intervention summary	Perspective	Economic analysis type	Conclusions
Binquet et al. (2019)	France	Neonatal screening of all newborns and treatment of infected vs. prenatal screening of all expectant mothers and monthly screening of uninfected (current system)	Health service	Incremental cost-effectiveness ratio (ICER) in terms of cost per additional outcome avoided	Prenatal screening is more effective than neonatal screening, even though the direct costs of the latter are lower.
Prusa et al. (2017)	Austria	No screening vs. prenatal screening of expectant mothers (current system)	Health service	Cost-benefit analysis (CBA)	Prenatal screening saves €323 per newborn.
Joss et al. (1990)	Scotland (UK)	Prenatal screening of expectant mothers vs. no screening (current system)	Health service	Cost-benefit analysis (CBA)	Positive cost-benefit outcome. Prenatal screening should be implemented.

3.1.1.2. Control of Toxoplasma gondii in slaughter pigs. Raw or undercooked pork meat has been recognized as a significant source of foodborne *T. gondii* infections in consumers. The parasite infects animal tissues and can survive through the slaughter and chilling processes. Control interventions against *T. gondii* in production systems can be implemented at various stages, including on the farm (e.g., controlling risk factors), at the abattoir (e.g., serological surveillance), or post-slaughter (e.g., cooking or freezing the meat). Three studies identified in this review, all from the Netherlands, discussed interventions at one or more of these production stages (Table 2). The first study conducted a break-even analysis to determine the maximum cost-per-farm for a proposed sero-surveillance sampling system at slaughter, followed by interventions for high-risk farms (van Asseldonk, van Wagenberg, & Wisselink, 2017). The analysis established the maximum cost based on a break-even point where the health benefits (measured in the monetized value of DALYs avoided) equaled the on-farm costs. This study determined the appropriate break-even points for on-farm interventions of varying efficacies. The second study developed a societal cost-benefit model and found that freezing high-risk meat products resulted in a net benefit to society, in contrast to on-farm biosecurity interventions, which resulted in a net societal loss with the costs borne by the farmers (Suijkerbuijk et al., 2018, 2019). The third study evaluated the efficacy (in terms of seroprevalence reduction) and the estimated annual costs of three on-farm interventions (neutering cats, covering feed, and pest control) across nine farms (Eppink et al., 2021). Using the cost threshold for on-farm interventions to break even at a societal level, neutering cats and covering feed were deemed economically viable.

3.1.2. Interventions for Taenia saginata

Four studies evaluating the economic impacts of *T. saginata* control measures were identified (Table 3). Two studies detailed the economic impact of *T. saginata* infections across multiple sectors: the healthcare sector, the veterinary public health sector, and the cattle/beef industry, using current meat inspection-based control strategies without comparing to any alternative intervention scenarios (Jansen, Dorny, Trevisan, et al., 2018; Laranjo-González et al., 2018). The principal distinction in approach was the method used to estimate healthcare costs. Laranjo-González et al. (2018) assessed healthcare costs through healthcare records (ICD-9-CM codes 123.2 and 123.3), which are likely to underestimate the actual costs. In contrast, Jansen, Dorny, Trevisan et al. (2018) estimated cases based on sales of anthelmintics, which may overestimate the *T. saginata*-specific infection burden, as the purchase of anthelmintics could have been triggered by infections with other parasites. The estimation of the number of people accessing healthcare or purchasing anthelmintics specifically for taeniasis greatly influenced the final estimate for Belgium.

The other two studies assessed alternatives to current meat inspection procedures. The first of these evaluated the annual costs of three control strategies compared with the existing meat inspection strategy (Jansen, Dorny, Berkvens, & Gabriël, 2018). The analysis accounted for costs across the cattle, veterinary, and health sectors over 1-year and 10-year periods. In this study from Belgium, the hourly meat inspection fee for abattoirs was €75. The inspection time dedicated specifically to the detection of cysticercosis was estimated at 15–60 s, which translates to a cost of between €0.31 and €1.25 per carcass. The cost of dealing with carcasses with cysticercosis, such as administration, supervision of deboning, freezing, or destruction of carcasses, was estimated at €37.5 to €112.5 per carcass, while a positive carcass also incurred a significant loss of value, estimated at 40–70%. Overall, these data show the significant economic impact of this disease on the industry. It should also be noted that, in addition to meat inspection as a control method, cysts could be detected and removed at later stages in the meat production and sale chain, such as in boning rooms, meat processing sites, and by butchers. However, no data on these control steps and activities are available, making an assessment of the overall contribution of these steps in the control of this parasite is difficult.

Implementing serological surveillance at slaughter, with or without meat inspection, was associated with a decreased prevalence and reduced societal costs over a 10-year timeframe. However, these strategies entailed an initial 3 to 7-fold increase in costs for cattle owners, slaughterhouses, and insurance companies in the first year, which diminished over the 10-year horizon as the prevalence of BCC decreased. Only the complete removal of meat inspection for BCC proved to be profitable for slaughterhouses in both the 1-year and 10-year time frames. While the sensitivity of meat inspection was a significant factor in the economic analysis, altering from a high-sensitivity to a low-sensitivity scenario did not shift the outcome from losses to profits for any sector.

The second study conducted a cost-effectiveness analysis (CEA) to evaluate the use of a risk-based meat inspection process in the UK from the meat industry's perspective, encompassing farmers, abattoirs, and government veterinary services (Chengat Prakashbabu et al., 2018). In this study, cattle were classified into high- or low-risk categories based on their movement history (whether they originated from a farm with previously detected infected animals) and the age and sex of the animal. A strategy involving enhanced meat inspection for high-risk animals

Table 2
Summary of findings on control interventions for T. gondii in slaughter pigs.

Author and year	Country	Intervention summary	Perspective	Economic analysis type	Conclusions
van Asseldonk et al. (2017)	NL	Risk-based serology at the abattoir for targeted biosecurity interventions on the farm, assuming 50% effectiveness, €50,000/DALY averted, and a 5% prevalence of *T. gondii* on a farm to enter the intervention	Societal (health sector, farmers, slaughterhouses)	Break-even analysis - Demonstrates the relationship between intervention efficacy and maximal allowable cost of intervention/farm to ensure the intervention is breaking even from the societal perspective	Maximal allowable cost/farm of €2981–4389 if only domestic consumer health impacts accounted for. If export market consumers' health accounted for, the maximum allowable intervention cost/farm €12,034–18,366.
Suijkerbuijk et al., 2018, 2019	NL	1. Increased biosecurity in farms 2. Freezing of beef, sheep, and pig meat	Societal (health, consumers, education, farmers, cat owners, pensions)	Social cost-benefit analysis (SCBA)	Freezing of some meats (steak tartare and sheep leg) would result in a **benefit** of €10.6 to 30.1 and 1.0 to 2.1 million, respectively. Increased biosecurity interventions would result in €1.0 to 2.5 million **loss**. Freezing of these two meats should be considered for public health and economic benefits.
Eppink et al. (2021)	NL	Farm-level interventions to reduce the level of *T.gondii* (control and neutering of cats, protection of feed, and professional pest control)	Cost-analysis	Cost analysis of intervention options and estimate of efficacy in terms of seroprevalence reduction	Cat neutering and covering of feed is considered viable using the break-even point estimated by van Asseldonk et al., 2017.

Table 3
Summary of findings on control interventions for T. saginata in beef cattle at slaughter.

Author and year	Country	Intervention summary	Perspective	Economic analysis type	Conclusions
Jansen, Dorny, Trevisan, et al. (2018)	Belgium	Current meat inspection	Societal (meat industry & health care plus insurance companies presented separately)	Economic impact	Societal losses of €2,093,317/year (extrapolated from sector-specific results).
Laranjo-González et al. (2018)	Spain	Current meat inspection	Societal (meat industry & health care)	Economic impact	Societal losses in Catalonia of €153,903/year.
Jansen, Dorny, Berkvens, and Gabriël (2018)	Belgium	Three alternatives (Ag-ELISA only, meat inspection plus Ag-ELISA on negative carcasses, no inspection) vs. current meat inspection	Societal (meat industry & health care plus insurance companies presented separately)	Cost-analysis	Ag-ELISA only increases detection of positive carcasses and leads to net savings over a 10-year horizon but incurs high initial net costs.
Chengat Prakashbabu et al. (2018)	UK	Risk-based meat inspection vs current procedure	Meat industry & Veterinary public health	Cost-effectiveness	Risk-based inspection had a positive incremental cost-effectiveness ratio (ICER) (savings per infected carcass detected).

from both high- and low-risk farms, while eliminating inspection for low-risk animals, resulted in an incremental cost-effectiveness ratio (ICER) of −£1300 per animal compared to current practices, indicating savings. Conversely, all other strategies yielded a positive ICER per detected animal. The classification of animals into risk categories was a pivotal variable in this analysis. Both studies identified cattle owners and slaughterhouses as bearing the most significant costs for any intervention strategy.

3.1.3. *Interventions for Trichinella spiralis*

Only one study evaluating control strategies for *T. spiralis* was identified (Table 4). Pre-harvest interventions, such as limiting the contact of pigs with other infected animals and controlling feedstuffs, are reported as the best methods to prevent pig infections (Pozio, 2019). In this context, Mirilovic et al. (2019) conducted a study to design, implement, and analyze the cost-benefit of a pest rodent control program aimed at managing *Trichinella* in pigs in Serbia. This program involved distributing poisoned baits (brodifacoum) around households and neighboring facilities. Costs for pest control were derived from a pilot intervention, while surveillance activity costs were obtained from the Serbian Veterinary Chamber. The estimated benefits resulted from the reduction in the number of *Trichinella*-positive pigs (and thus condemned carcasses), reduced carcass screening, and fewer human trichinellosis cases. The expected benefits from implementing the pest control program were €5,101,247.06 over 10 years, with a NPV of €1,652,182.14, suggesting that the program is economically justified. However, the paper does not clearly explain the source of data on intervention effectiveness in terms of the reduction in human cases. The concern about not explicitly identifying the data sources used to assess the effectiveness of the interventions in reducing human cases is valid. It is critical to address whether any additional costs incurred by farmers due to these interventions were evaluated, as well as whether other biosafety intervention measures were considered. Clearly, the study by Mirilovic et al. (2019) should have enhanced the transparency of its methodology by clearly defining its data sources and assumptions.

3.2. *Economic evaluation methods utilized for control of meatborne parasites*

Multiple economic evaluation frameworks applied to the control of meatborne parasites in the European context were identified. This section of the results addresses each framework identified and the commonalities in how these frameworks have been applied across different interventions, countries, and parasites. Given that economic evaluation frameworks are intended to support decision-making through comparative analysis (Husereau et al., 2022), this section only includes manuscripts that feature a comparator intervention, thereby excluding the two papers that solely assess the current economic impact of disease under the status quo (Jansen, Dorny, Trevisan, et al., 2018; Laranjo-González et al., 2018). The methodologies employed for economic evaluation in the nine studies with comparator interventions encompassed cost analysis (2), break-even analysis (1), CBA (4), and CEA (2). The results from the quality assessment criteria checklist indicate that while the objectives of the studies, populations, intervention scenarios, costs of interventions, and economic outcomes are well described and justified, the justification of the costs and health burdens averted, the use of discounting where appropriate, and the conduct of sensitivity analysis were reported less consistently (Supplementary Material S4).

3.2.1. *Cost-analysis*

A cost analysis evaluates the costs of interventions, including medical offset expenses, but does not include clinical benefits. Two manuscripts compared the costs and benefits incurred by various intervention options for *T. saginata* and *T. gondii*, respectively, but without a summative assessment of the cost-benefit ratio, NPV, or internal rate of return, and were therefore classified as cost-analysis studies (Eppink et al., 2021; Jansen, Dorny, Berkvens, & Gabriël, 2018). These two studies addressed different parasites and contexts: *T. saginata* in Belgium and *T. gondii* in the Netherlands. Jansen, Dorny, Berkvens, and Gabriël (2018) provided cost data for four intervention scenarios modeled over a 10-year time horizon from the perspectives of farmers, abattoirs, insurance companies, and the healthcare sector. Eppink et al. (2021) assessed the costs of on-farm interventions over a single year from the farmer's perspective.

3.2.2. *Break-even analysis*

Break-even analysis, which determines the threshold cost at which the costs of an intervention equal the potential costs of non-intervention, is relatively uncommon in health economics, though some examples exist (Comans, Brauer, & Haines, 2009; Hatch, Daniels, Glerum, & Higgins, 2017; Martinazzi et al., 2022). One study utilizing this

Table 4
Summary of findings on control interventions for *T. spiralis*

Author and year	Country	Intervention summary	Perspective	Economic analysis type	Conclusions
Mirilovic et al. (2019)	Serbia	Pest control on the farm	Societal (farm, veterinary public health, & health sector)	Cost-benefit analysis (CBA)	On-farm pest control demonstrated a positive benefit-to-cost ratio under the two scenarios modeled.

approach was identified, which aimed to determine the maximal cost for an on-farm intervention to break even with the savings from averted human *T. gondii* infections at various intervention efficacy levels (van Asseldonk et al., 2017). This analysis, utilizing a short time horizon (1 year), demonstrated the impact of the monetary value assigned to a DALY averted on the break-even point for an intervention.

3.2.3. Cost-benefit and social cost-benefit analysis (CBA and SCBA)

Cost-benefit analysis (CBA) is a highly flexible and well-established framework that compares the monetized costs and benefits of an intervention to determine its net benefit (or cost), generally presented as a NPV. Net present value (NPV) represents the current monetary value of future monetary flows. The framework converts all costs and benefits into monetary units, making it highly adaptable yet reliant on value judgments for the monetization of non-monetary goods and services, such as the value of human lives or environmental and social externalities without market values. Four manuscripts utilizing CBA were identified: (Joss, Chatterton, and Ho-Yen (1990) and Prusa et al. (2017) examined the cost-benefit of *T. gondii* screening in pregnant women (in Scotland and Austria, respectively). Both studies compared the costs to the healthcare sector for antenatal screening protocols against the preventable costs (to healthcare, education, family, and productivity losses) related to congenital toxoplasmosis, concluding that screening was a cost-saving approach. Mirilovic et al. (2019) employed a CBA to evaluate the economic efficiency of systematic rodent control in Serbia for controlling *T. spiralis* in pigs, indicating profitability. However, the justification for the averted costs and health burden (i.e., the program's effectiveness) was not clearly reported. No discounting was applied despite the analysis spanning a 10-year time horizon.

Social cost-benefit analysis (SCBA) is an extension that explicitly accounts for broader social and environmental impacts, showcasing the framework's adaptability for analyzing interventions with costs and benefits across multiple sectors and actors. Suijkerbuijk et al. (2019), in an analysis detailed in Suijkerbuijk et al. (2018), utilized an SCBA to assess the cost-benefit of toxoplasmosis control from a societal perspective (specifically consumers, producers, and government — healthcare and education) over a one-year time horizon. The freezing of high-risk meat products (steak tartare and leg of mutton) was associated with net benefits to society and remained positive in scenario and sensitivity analyses. Conversely, biosecurity interventions resulted in a net loss to society. The quality assessment criterion indicates that this study was well reported, with clear and justified objectives, population, and interventions, documented costs, modeled health burdens averted through a quantitative microbial risk assessment, and a performed and reported sensitivity analysis.

3.2.4. Cost-effectiveness analysis (CEA)

A CEA compares the net costs and benefits of an intervention, where benefits are measured in non-monetary units related to health. It adopts an extra-welfarist or capability approach, valuing the equal gain of health for all individuals. The summary measure of CEA is reported as a cost-effectiveness ratio (CER) or incremental cost-effectiveness ratio (ICER) between the monetary cost and the gain in health units. The CER is evaluated against pre-set thresholds of what is considered cost-effective, such as those provided by the WHO-Choosing Interventions that are Cost-Effective (WHO-CHOICE) program or set by national HTA bodies like the National Institute for Health and Care Excellence (NICE) in the UK. These thresholds are based on the underlying assumption about the opportunity cost of implementing a program, suggesting that investment in one area will result in a related opportunity cost in health gains from another health investment (Evans, Tavakoli, & Crawford, 2004; Leech, Kim, Cohen, & Neumann, 2018).

Two manuscripts were identified that used CEA to evaluate FBP control options. Eppink et al. (2021) assessed the ICER of a neonatal screening strategy versus the current French antenatal screening program from the perspective of the national health insurance system. The analysis included direct medical costs (in euros) incurred by the screening and treatment protocols, with outcomes of interest being *Toxoplasma*-specific adverse events and global adverse events (including iatrogenic events). A 1 and 15-year time horizon was utilized in this analysis, with a 3% discounting rate applied to the long-term analysis. Uncertainty was incorporated through ranges around each parameter, and sensitivity analysis was used to identify influential variables. Chengat Prakashbabu et al., (2018) used a CEA approach to evaluate four risk-based meat inspection protocols against the current baseline of inspecting all carcasses. Carcasses would be allocated to normal, enhanced, or no inspection based on their risk categorization. The CEA, performed from the industry and public veterinary services perspective over a 1-year time horizon, included costs related to the inspection process and processing or devaluation of carcass meat, with an outcome of the number of infected carcasses detected. No direct human health outcomes were evaluated in this manuscript, though the detection (and thereby treatment or condemnation) of infected carcasses would result in lower human infection pressure. Uncertainty in parameters was incorporated through a stochastic modeling process, and the ICER presented the most likely, best-, and worst-case scenarios. The best methods for diagnosing taeniasis in humans are perianal swabbing (80–88.9% effective) and fecal examination (40–44.4% effective) (Cabaret, Geerts, Madeline, Ballandonne, & Barbier, 2002). However, since there is no requirement to report human cases in Europe, establishing the true prevalence of the parasite is difficult and is based mostly on indirect indicators, such as the use of taenicides in the human population (Dorny & Praet, 2007) or the levels of parasitism in the bovine population. Using the latter method, Prakashbabu (2018) has estimated the prevalence of human taeniasis in Europe to be between <0.01% and 10%. The wide range of this estimate is due to the potential for low prevalence levels of taeniasis in the human population to still infect large numbers of cattle. The flooding or irrigation of pasture land with contaminated water, or the use of sewage sludge for soil fertilisation, could also expose large numbers of cattle to eggs from only a small number of taeniasis cases due to the production of large numbers of eggs by the parasites, as it is estimated that the mean daily excretion of eggs by an infected human individual ranges from 150,000 to millions of eggs daily (Bucur, Gabriël, Van Damme, Dorny, & Vang Johansen, 2019; OIE (World Organisation for Animal Health), 2005). Furthermore, evidence and reason indicate that some human infections seen in Europe may have been acquired in other countries, although accurate estimates for this figure are not available (Laranjo-González et al., 2017; Trevisan et al., 2018). It is worth noting, however, that irrespective of where the infections occurred, the economic burden of the direct (diagnosis and treatment of human cases) and indirect costs (e.g., losses at meat inspection, contamination of the environment, increased infection rates in humans) of the disease will still fall on the European host countries. In addition, data on bovine cysticercosis within the EU indicates ongoing active transmission of the parasite, highlighting the need to ensure appropriate control and surveillance in the European context.

4. Discussion

This scoping review identified 12 studies that aimed to economically evaluate meatborne parasite control in Europe. The studies highlight the potential benefits in terms of health burden reduction or costs averted through the implementation of key control strategies for these parasites. Interventions demonstrating positive economic outcomes (i.e., improved cost-effectiveness over a comparator, positive benefit-cost ratio, positive NPV) included neonatal screening for toxoplasmosis in France (Binquet et al., 2019), Austria (Prusa et al., 2017), and Scotland (Joss et al., 1990), freezing of high-risk meat products for toxoplasmosis control in the Netherlands (Suijkerbuijk et al., 2019), the use of Ag-ELISA as a detection technique for *T. saginata* in cattle at slaughter in Belgium (Jansen, Dorny, Berkvens, & Gabriël, 2018), implementation of a risk-based meat inspection procedure for *T. saginata* in UK cattle

(Chengat Prakashbabu et al., 2018), and on-farm pest control for *Trichinella spiralis* in Serbia (Mirilovic et al., 2019). However, the absence of consistent methodologies for the economic assessment of control strategies results in difficulty comparing these results with each other or with other disease control strategies for proper resource allocation decisions.

This situation starkly contrasts with the field of HTA, where guidelines for conducting and reporting economic analyses exist. These guidelines enable healthcare providers, whether public or private, to make investment decisions from an economic perspective. Examples of national guidelines for conducting economic analysis of healthcare technologies include those provided by the UK's NICE (NICE, 2022) and the WHO (WHO, 2003).

Since food safety interventions involve a mix of public and private sector actors, with benefits primarily accruing in the health sector, relying solely on CEA with a single sector metric as an outcome (e.g., $/DALY averted or similar) may not be the most suitable approach for this field. The fact that food safety interventions may be conducted at different parts of the value chain, including the consumer node (for example, perinatal screening for *T. gondii*), highlights the importance of being able to compare the economic efficiency of interventions conducted at different points. A SCBA, presenting the net monetary benefit to society alongside sector-specific gains or losses, may be a better proposal for assessing food safety interventions, as suggested by Suijkerbuijk et al. (2018) and Robertson et al. (2018). If guidelines for such were produced, they should include an impact inventory, as similarly proposed by the Second Panel on Cost-Effectiveness in Health and Medicine. This inventory would act as a checklist of outcomes to be included in economic evaluations, covering both health and non-health aspects. Reporting guidelines such as the CHEERS (Husereau et al., 2022) are also necessary to promote standardization and comparability of assessments across different food safety hazards and interventions. Moreover, the consistent use of sensitivity analysis to identify the most influential variables within an analysis should be emphasized. This approach would facilitate the *ex-ante* assessment of control strategies among countries with varying epidemiological and economic contexts.

Finally, the role of food safety regulations in the prevention of the transmission of meatborne parasites cannot be overstated. Specific regulations, such as Regulation (EU) 2015/1375 Commission Implementing Regulation 1375, 2015) on official controls for *Trichinella* and meat inspection in slaughterhouses for cysticercus detection, as detailed in Regulation (EU) 2019/627 (Commission Implementing Regulation, 2019), are critical. Beyond these specific measures, the EU has established a comprehensive legal framework to ensure high standards of food safety across its member states and general food safety regulations, such as Regulation (EC) 178/2002 Regulation (EC, 2002)) significantly influence food safety practices, hygiene standards, and surveillance systems, thereby also helping to prevent the transmission of foodborne parasites.

5. Conclusions

This scoping review has uncovered a scarcity of economic evidence for current control programs targeting meatborne parasites, revealing that a variety of approaches have been utilized for economic evaluations. However, there is a notable lack of standardization in methods and reporting. These limitations restrict our ability to formally compare the economic efficiency of different control strategies or to understand how these strategies might perform in countries with different epidemiological contexts. Consequently, decision-making is impaired due to the lack of comparable data. While initiatives such as the Global Burden of Disease, the FERG, and the Global Burden of Animal Diseases are facilitating the generation of data on the burden of diseases, including meatborne parasites, we strongly recommend the development of guidelines for conducting and reporting economic analyses of food safety interventions. These guidelines should consider the cross-sectoral nature of potential interventions and the costs and benefits that accrue.

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CRediT authorship contribution statement

N. Dadios: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **P.H. Imazaki:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **C. Millins:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **L.F. Thomas:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Data availability

All data have been incluided in the Supplementary materials

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Appendix A. Supplementary data

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