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Review Article

Review of Biological and Chemical Health Risks Associated with Pork Consumption in Vietnam: Major Pathogens and Hazards Identified in Southeast Asia

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Foodborne illness is a difficult public health burden to measure, with accurate incidence data usually evading disease surveillance systems. Yet, the global scope of foodborne disease and its impacts on socioeconomic development make it an important health risk to address, particularly in low- and middle-income countries. In Vietnam, rapid development has seen large-scale commercial operations rise to coexist amongst traditional value chains in the food landscape, most of which operates outside of a domestic food safety network. Rapid socioeconomic development has also seen an increase in meat consumption, with pork being the most consumed meat product nationally. Expanding pork value chains, and the increasing diversity of actors within them, facilitates the growth and propagation of hazards which are passed onto Vietnamese consumers. In order to guide illness prevention and governance efforts, this review was conducted to examine health risks associated with pork consumption in Vietnam. Synthesis of the available literature provided evidence that *Salmonella* spp. bacteria are a major cause of foodborne illness from Vietnamese pork products. However, contaminants of global concern, including *Salmonella* spp. and *Trichinella spiralis*, occur alongside those considered neglected tropical diseases, such as *Taenia solium*. Infections and complications associated with ingestion of *Streptococcus suis* bacteria are also an issue, with *Streptococcus suis* infections usually limited to occupational infections amongst meat handlers in modernised value chains. A risk factor underscoring transmission of *Trichinella spiralis*, *Taenia solium*, and *Streptococcus suis* in Vietnam that emerges from the literature is the consumption of dishes containing raw or undercooked pork. Available data indicates that infections associated with raw pork consumption disproportionately affect men and people in regional mountainous areas of northwest Vietnam, where many of Vietnam's ethnic minority communities reside. In addition, epidemiological data from recorded disease outbreaks that result from raw pork consumption demonstrate that these outbreaks usually follow major sociocultural events such as weddings, funerals, and Lunar New Year celebrations. Potential health impacts resulting from residues of antibiotics and heavy metals are also cause for concern, though the direct links between chemical contaminants in food and the development of disease are difficult to conclusively deduce.

1. Introduction

The World Health Organization (WHO) estimates that the global burden of foodborne illness is at a magnitude comparable to other major global health issues including HIV/AIDS, malaria, and tuberculosis [1]. Representing a multifaceted threat to public health across society, food contamination and foodborne illness stems from a myriad of underlying chemical and biological agents, with the adverse effects of unsafe food disproportionally affecting children. Specifically, the WHO estimates suggest that approximately 40% of the global foodborne illness burden is borne by children under five years of age [1, 2]. Recurrent bouts of foodborne illness in children can be particularly severe and have prolonged health impacts, as nutrients crucial to childhood growth and development processes are redirected to resource-intensive immune responses [3]. Resulting symptoms of gastrointestinal disease and infection have also been demonstrated to interfere with other outcomes such as education, with mass de-worming programs significantly

increasing school attendance rates [4]. Decreased rates of participation in education and employment similarly impact working age adults, who may experience foodborne illness themselves or take leave to care for others. Monetary or material loss from decreased work participation can exacerbate poverty by straining already limited resources for low-income families and individuals [2]. Culminating on a larger scale, these financial losses represent a significant burden borne by the macroeconomy of nation states. As such, food safety is being increasingly seen as a socioeconomic and development issue, particularly in low- and middle-income countries [1, 2].

Prevalence rates of foodborne illness are a difficult public health concern to measure, particularly in countries with emerging health surveillance systems. At present, robust figures to compare levels of foodborne disease and subsequent impacts between different states remain largely unavailable [1]. Accurate data on foodborne illness is difficult to ascertain, in part, because most people who suffer from foodborne illness will do so privately [2]. Even in countries with advanced surveillance systems to monitor notifiable diseases, only a small percentage of those suffering from foodborne illness will seek medical care [2]. Thus, acquiring accurate data on foodborne illness is particularly challenging for developing countries where surveillance systems are less established, as cases in patients who do seek medical care are less likely to be recorded or reported to wider health authorities [2]. In order to define the scope of foodborne illness rates, the WHO leveraged existing data and expertise to publish the first global estimates of foodborne disease by the region in 2015. The report acknowledged data-related challenges and advised that the resulting estimates were conservative, although it was a rare quantification of an often-neglected health issue. The results highlighted a considerable disparity in health outcomes related to food safety between high- and low-income countries [1], which mirror existing inequalities in other facets of health. However, while available research reveals that issues surrounding food safety disproportionally affect the world's poor, lower levels of foodborne disease in developed countries substantiate that much of the global foodborne illness burden is preventable [1].

In Vietnam, local food systems are experiencing a period of rapid change, mirroring the fast-paced development occurring across wider Southeast Asia. At present, Vietnam's food industry is a mixture of traditional smallholders and emerging enterprises, though there are regional variations. Traditional food systems and value chains dominate the market in the north, with northern Vietnamese consumers typically preferring to purchase fresh produce at traditional markets and wet markets over chain stores [5]. Food in the markets is generally locally sourced, and associated value chains are dominated by small-scale producers [6–8]. For instance, it is estimated that smallholders are responsible for 83% of domestically produced pork meat in Vietnam [5, 8]. However, in line with Vietnam's transition from a low- to lower middle-income country, larger-scale commercial operations have emerged and started integrating into the local food systems [7]. In Ho Chi Minh City, in particular, larger-scale wholesalers have started to become more prominent market players [5]. Supermarkets have also started to emerge as authorities have pushed for the development of a food landscape which imitates those found in developed nations [9]. However, across the country, demand for traditional markets remains significant, leaving supermarkets in Vietnam with one of the lowest market shares in all of Southeast Asia [5, 9].

The current food landscape in Vietnam makes it a particularly difficult sector over which to govern safety standards. In 2010, the Vietnamese government introduced world standard food safety protocols, with responsibilities for oversight shared across three major government ministries at central and provincial levels [5, 9]. This oversight is primarily risk-based and utilises a model centred around inspection and testing [5]. However, government efforts to develop and regulate the food sector, including the introduction of good practice accreditation schemes such as "VietGAP," have had limited impact [10–12]. With so many smallholders and limited resources, an effective domestic surveillance system to monitor food production and safety has not been established [5, 8]. For instance, despite government guidelines around the administration of antimicrobials to livestock, a significant amount of unsupervised antimicrobial use occurs in Vietnam's agricultural sector [13–15]. In addition to concerns around fostering antibiotic resistance (AMR) in zoonotic bacteria, unsupervised administration of antibiotics can leave antibiotic residues in meat products destined for human consumption. These and other chemical contaminants present potential health risks to consumers. However, the limited amount of testing that has been undertaken by the Vietnamese Food Authority (VFA) indicates that biological hazards are the most frequently recorded health risk in domestically produced food [5].

The real incidence of foodborne illness in Vietnam is largely unknown, though concern over food safety is salient in the community. Registered cases of foodborne illness and associated deaths are recorded by the VFA, yet the level of data that is captured is low [5]. For instance, in the first half of 2014, only 21 outbreaks of foodborne illness were documented, affecting a recorded 714 individuals in a population of over 90 million people [16, 17]. Further, in approximately a quarter of cases registered, the pathogen or source of illness is classed as "unknown" [5]. Nevertheless, the available public health data reflects VFA estimates, which suggest that biological hazards represent the largest source of foodborne illness nationally [5]. Consumer concerns, however, are more focused on chemical hazards; specifically, chemical additives and pesticides that might facilitate the development of cancer [5, 11]. While there are chemical hazards present in domestically produced food, the link between chemical residues and illness is not as robust or conclusive as in the case of biological hazards. Part of this difference in perceptions of risk between public health bodies and the public lies in the approach to risk communication adopted by the national media [11]. Though foodborne hazards have garnered widespread attention in Vietnam, biological hazards in foods remain

underreported, whereas chemical hazards are more likely to attract headlines and speculation [11].

This review will examine pathogens and hazards that have the ability to cause illness following the ingestion of pork products in Vietnam. Economic development has driven demand for animal products, with pork meat becoming particularly prominent in Vietnamese diets [5, 6]. Accounting for 70% of all meat consumed nationally, pork consumption per capita in Vietnam is the third highest in the OECD [18]. However, as is the case in other developing countries, raw food handling rarely meets good practice standards [15]. Pushes to transform the pork value chain, and the wider food industry, have looked to normalise Western-style paradigms with little consideration for local contexts and practices [9]. To date, these efforts have not achieved sustainable and equitable improvements in pork safety. Thus, there is an urgent need to develop context-appropriate, effective, and low-cost solutions [1, 9, 11]. By reviewing the scope and burden of different pork-borne health risks in the literature, this paper looks to identify high-value targets for future food safety objectives, highlighting relevant pathogens and hazards, as well as gaps in the current research.

2. Methods

A pilot search of the literature was undertaken to identify key terms and inform subsequent research, with a second search conducted using the PubMed database. English terminology and phrases used during the search included "pork AND illness AND Vietnam," "pork AND disease AND Vietnam," and "pork AND health risk AND Vietnam." However, due to a limited number of search results, the terminology was widened to "pork AND illness AND Southeast Asia," "pork AND disease AND Southeast Asia," "pork AND health risk AND Southeast Asia," and "pork meat AND infection AND Southeast Asia." Pathogens known to infect humans through pork consumption were also used as part of pathogen-specific search phrases, including "*Salmonella* AND Vietnam AND pork meat" and "*Escherichia coli* AND Vietnam AND pork."

As Vietnam transitioned from a low-income country to a lower middle-income country in 2008, only articles published between 2008 and 2018 were considered as relevant for inclusion. With relevant articles identified, aggregate search results were collated for analysis, and duplicate articles removed. The final list of articles was screened for eligibility by the main author (MC), and data pertaining to, or extracted from, the sources were managed using an evidence table. When articles were excluded after only the abstract had been read, this was recorded. However, articles read in full had major data points extracted including the objective of the study, study location, population, sample size, testing method undertaken, and outcome. The literature considered for inclusion in the review comprised both qualitative and quantitative studies, including clinical studies following the diagnosis and treatment of a cohort of patients. However, studies written exclusively on subjective perceptions of risk held by consumers or other actors in the pork value chain were excluded from the study. Pearling methods were also utilised to identify articles for inclusion from the reference list of relevant articles.

As the search had been extended to include studies from wider Southeast Asia, articles were screened to ensure the context in which the study was undertaken was comparable to Vietnam. As such, studies from Hong Kong and Singapore were excluded from the review, as local pork value chains do not mirror the pork value chains in Vietnam. However, studies from southern China, Thailand, Lao People's Democratic Republic (PDR), and Cambodia were considered for inclusion. These geographic regions were considered comparable to Vietnam given their geographic proximity, shared climate, level of development, the nature of their pork production industries, and some shared culinary customs. Regions of Lao PDR and China that share a border with Vietnam were considered particularly relevant, as they share some ethnic minority populations, and some cross-border pig trade occurs.

Research studies selected for inclusion demonstrated a direct health risk to humans through pork consumption, as a result of conditions in which pigs were raised and slaughtered. Here, direct health risks were considered to be risks that had the potential to bring on acute illness, either shortly after consumption or through long-term toxic or accumulative effects. As such, articles discussing health risks pertaining to the nutrient profile of pork or the role of diet in the development of noncommunicable or chronic disease were excluded from the study. Faecal coliforms or other pathogens that can be introduced to pork products by human handling only were also considered beyond the scope of this review. As customers regularly touch pork meat at markets and in retail outlets in order to evaluate potential purchases, it is difficult to deduce whether pathogens that can only be introduced through human handing were done so by actors in the value chain or by end-stage customers. Instead, included articles detailed pathogens that colonise pigs and pork meat directly from rearing and slaughter practices, sometimes with reference to how transport and aspects of the retail environment can facilitate cross-contamination and higher loads of these pathogens. Also beyond the scope of the review were articles detailing health risks that are only amplified by proximity to live pig production (i.e., Japanese encephalitis). The literature examining pathogens and contaminants posing a threat to the health of pigs only were also excluded.

Articles discussing pathogens that can be contracted directly from pork consumption were excluded if consumption of pork meat was not explored as a potential route of infection. Hence, articles detailing occupational exposure only to relevant pathogens were excluded from the study (Figure 1).

3. Results and Discussion

A variety of risks to the health of Vietnamese pork consumers were identified through the literature. Broadly, these risks fall into two categories: biological pathogens and chemical risks. Major risks detailed in the literature are

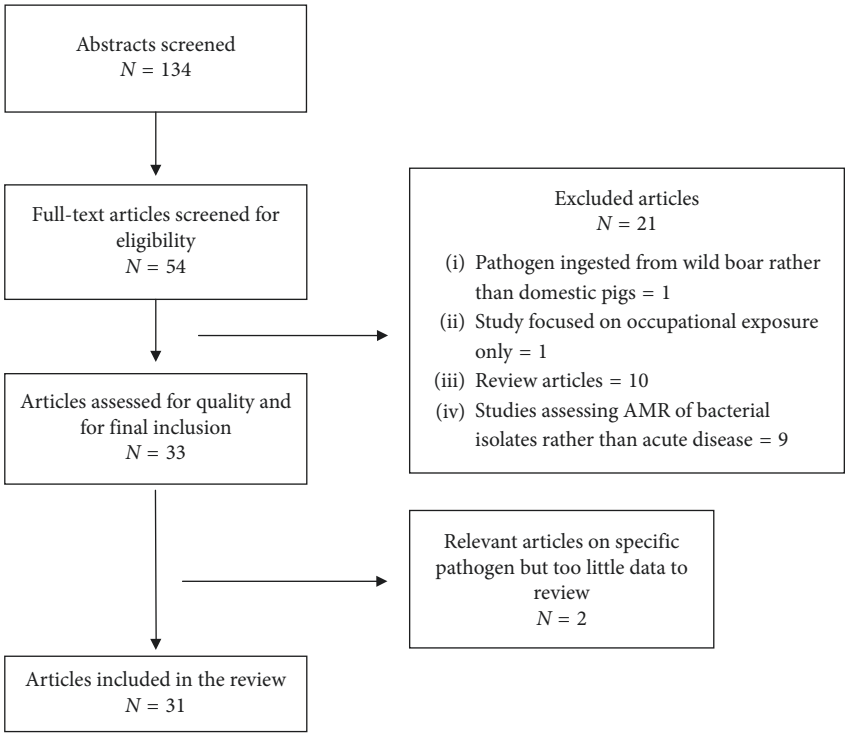

Figure 1: Flow diagram displaying systematic search results and reasons for exclusion.

discussed below according to type of hazard and phylogenic kingdoms where appropriate.

3.1. Bacteria

3.1.1. Salmonella spp. *Salmonella* spp. are zoonotic bacterial pathogens that can colonise the gastrointestinal tract of pigs and cause disease in humans. The two species, *Salmonella bongori* and *Salmonella enterica*, have many subspecies and serovars to group and delineate different characteristics. One major delineation is between "typhoidal" and "nontyphoidal" *Salmonella* [1, 2]; "typhoidal" *Salmonella* bacteria can cause typhoid fever and are adapted to be transmitted horizontally between humans, whereas "nontyphoidal" *Salmonella* can colonise humans and animals [1]. In pigs, most serovars of nontyphoidal *Salmonella* are commonly carried asymptomatically in the gastrointestinal tract. As such, good slaughtering and processing practices must be enacted to prevent contamination of the pig carcass with the contents of the bowel [19]. Human ingestion of food contaminated with a sufficient load of nontyphoidal *Salmonella enterica* can result in "salmonellosis," a gastrointestinal infection with symptoms including abdominal cramps, fever, vomiting, and diarrhoea [1, 2]. While cases of salmonellosis are often self-limiting, severe cases can result in death, with global estimates suggesting that nontyphoidal *Salmonella enterica* is the leading cause of death from a diarrheal disease agent [1].

The literature exploring *Salmonella* spp. on pork products in Vietnam is typically concerned with testing pork at various stages throughout the value chain to establish levels of *Salmonella* spp. contamination. In Vietnam, there are many small-scale pig producers generating independent value-chain linkages. As such, levels of *Salmonella* spp. contamination can vary widely according to the different practices adopted by independent actors within that chain. Results from studies exploring levels of *Salmonella* spp. on pork products vary accordingly. Studies of pork products conducted across Vietnam have found *Salmonella* spp. prevalence rates ranging from 25.0% to 72.7% [7, 19–21]. A major source of variation between studies is the level of cross-contamination that occurs between pork product slaughtered or sold in the same facility. A study in Hung Yen province established that 41.7% of carcasses in slaughterhouses were positive for *Salmonella* spp., though the presence of *Salmonella* spp. other surfaces provided a significant risk for further cross-contamination [19].

How the prevalence of *Salmonella* spp. on pork translates into actual cases of salmonellosis in Vietnam is difficult to infer. As previously mentioned, the WHO report detailing the first estimates of global and regional foodborne illness burdens acknowledged that data on foodborne illness are often underestimated [2]. Many individuals who experience symptoms will choose seeking treatment and recovery in private, resulting in the majority of cases going unrecorded by medical practitioners, even where good surveillance systems exist [2]. Still, the resulting WHO report estimated that, in the Western Pacific Region containing Vietnam, the annual incidence of foodborne salmonellosis was 1% (*R*: 0.2–7%) [2]. However, other research has estimated that the *Salmonella* spp. prevalence rates on raw pork, in combination with reported preparation methods (such as using the same knife and chopping board for raw and cooked pork),

put the annual risk of Hung Yen consumers contracting salmonellosis from boiled pork at 17.7% [19, 20]. The marked gap between these two estimates highlights the difficulties in enumerating the burden of foodborne illness, particularly if attempting to capture the impact of diverse actors and handling practices.

Transportation and handling of pork meat can further compound the risk of salmonellosis. Typically, pork is brought to traditional markets straight from the slaughterhouse, whereas supermarket pork usually requires additional time and added handling before reaching the consumer. However, given that pork is generally transported to traditional markets in bamboo baskets on motorbikes, and markets operate in ambient temperatures, cross-contamination and bacterial growth is easily facilitated [7]. Supermarkets, on the other hand, utilise cold chain transport and packaging in an effort to inhibit bacterial growth and limit further contamination.

3.1.2. Streptococcus suis. *Streptococcus suis* is a zoonotic pathogen that is typically spread between pigs via vertical or horizontal transmission [22]. Thirty-three serotypes of *S. suis* have been identified, with some that cause disease in young or embryonic piglets carried asymptomatically by adult pigs in the upper respiratory, gastrointestinal, and genital tracts [22, 23]. Of the 33 serotypes identified, serotype 2 (*S. suis* 2) is the most frequently involved in human disease [23, 24]. *S. suis* is primarily considered an occupational pathogen, and infections are common amongst those who work in pig rearing or slaughter [25]. However, *S. suis* can also infect humans through the consumption of raw, undercooked and fermented pork dishes [24, 25]. People with *S. suis* infections typically display symptoms such as fever, fatigue, neck stiffness, and acute meningitis [25]. Auditory effects such as hearing loss and tinnitus are also common amongst those with acute meningitis [25, 26]. While symptoms of tinnitus usually subside, attributed hearing loss is often permanent [27]. Complications in more severe cases frequently include sepsis, septic arthritis, and endocarditis, which can result in death [25]. The mortality rate as a result of *S. suis* infections in Southeast Asia varies significantly amongst clinical studies, though the development of sepsis amongst participants positively correlates with death [25–27].

S. suis is the most common cause of bacterial meningitis in Vietnam, and a leading cause of meningitis in Southeast Asia, where infection through consumption of raw pork is more common than in other regions [23, 26, 28]. Epidemiological studies in Southeast Asia have demonstrated that some *S. suis* infections can be attributed to occupational exposure, though occupational exposure alone cannot explain a significant proportion of observed cases. In Ho Chi Minh City, one study following 101 confirmed *S. suis* infections found that, in 25.7% of cases, eating high-risk raw pork dishes was the only risk factor reported by the patient [23]. In addition, while research on *S. suis* cases in rural Vietnam is slim, research from rural Thailand proposed that approximately 70% of *S. suis* infections investigated were linked to the consumption of raw pork [24, 29]. The occurrence of ritualised consumption in Thailand has been suggested, with incidences of *S. suis* food poisoning peaking over months where crop harvesting is celebrated with food [24].

Conclusions from epidemiological studies which implicate raw pork consumption as a route of transmission have been supported by genetic research. A study examining pigs slaughtered in southern Vietnam determined 41% of sample pigs harboured *S. suis* in their tonsils, with 8% of pigs harbouring pathogenic serotype 2 specifically [22]. The *S. suis* 2 isolated from the pigs were compared to isolates from patients with bacterial meningitis. It was found that virulence markers present in the pig isolates mirrored those in samples isolated from patients where consumption of pork was suspected to be the route of infection [22]. The *S. suis* 2 isolated from the carcasses and their genetic similarity to isolates from patients indicate that raw pork consumption may be a common route of infection in Vietnam. However with the ongoing development of health services and surveillance systems in the region, particularly in rural areas where raw pork consumption is more common, it is likely that the prevalence of *S. suis* infection remains significantly underestimated [24].

Epidemiological studies point to additional risk factors that may affect the risk of *S. suis* infection. Takeuchi et al. [29] traced confirmed *Streptococcus suis* cases in regional northern Thailand back to sites of exposure and determined that infection only occurred sporadically amongst people who would all share the same pork product. As such, Takeuchi et al. [29] concluded that infection with *S. suis* via the oral route may require predisposing factors or health comorbidities. Other studies documenting *S. suis* cases have confirmed that unfavourable health indicators, particularly alcoholism and diabetes, are relatively high amongst participants [25, 27, 28]. In addition, *S. suis* infections are consistently shown to occur at a higher incidence amongst males than females [23, 25, 28]. Age is another correlate, with recorded cases usually occurring in adults over approximately 50 years of age [23, 25]. Weather may be an additional influence over the number of infections observed, with two Hanoi-based studies seeing an increase in infections over the summer months [23, 28]. However, in Ho Chi Minh City, where seasonal weather is less varied, little disparity in case numbers occurs between seasons [23, 28].

In an effort to reduce the illness burden associated with *S. suis* infection in regional northern Thailand, Takeuchi et al. [29] launched a public health campaign in 2011 to highlight the risks associated with consumption of raw pork. The campaign achieved early success, and for the first two years, recorded cases of *S. suis* infection dropped to approximately a third of 2010 levels. However, by 2013, *S. suis* infections began increasing, reaching approximately half of 2010 levels before the study was terminated in September of that year [29].

3.2. Protozoa

3.2.1. Taenia spp. *Taenia* species, commonly known as "tapeworm," are zoonotic parasites whose intermediate

hosts include domestic animals such as pigs, cattle, and dogs [30, 31]. Two species present in Southeast Asian pig populations and known to colonise humans are *Taenia solium* and *Taenia asiatica* [30–33]. The lifecycle starts with pigs inadvertently ingest fertilised *Taenia* spp. eggs or proglottids (sexually reproductive segments of the tapeworm which contain eggs) present in their surrounding environment. Upon ingestion, the eggs will develop into larvae in the porcine gastrointestinal tract. The larvae will then penetrate through the wall of the digestive tract and encyst in other tissues of the body, a condition known as "cysticercosis." Subsequent human consumption of cystic pork meat sees the larvae establish in the human intestinal system and mature into an adult, referred to as "taeniasis" [30, 31]. Considered a neglected tropical disease, taeniasis can be asymptomatic or induce mild symptoms including nausea, abdominal discomfort, and diarrhoea [31]. A key sign of infection is passing proglottids and eggs through the faeces, which facilitates transmission to new hosts and completes the lifecycle of the parasite.

A variety of factors and behaviours facilitate the transmission of *Taenia* spp. and increases the risk of human taeniasis. Human taeniasis usually occurs in areas with low access to hygienic sanitation and where the practise of open defecation is common [30–32, 34]. In areas that practise open defecation, contaminated human faeces allows *Taenia* eggs to disperse throughout the environment where pigs are more likely to come into contact with them; the risk of transmission is further amplified in areas where pigs are not penned but allowed to roam and graze freely [30–32, 34]. Adequate application of heat during the cooking process can inactivate larvae in pork tissue, thus consumption of meat that is undercooked or raw also significantly increases risk of contracting taeniasis [30, 32]. Research in the Phongsaly Province of Lao PDR has demonstrated that local consumption of raw and undercooked pork dishes, typically eaten around rituals and milestone events, has facilitated a hyperendemic region of *T. solium* infection [32, 33]. In one hyperendemic village studied, the taeniasis prevalence was recorded at 26.1% (95% CI = 18.2–35.9) where other research has put the baseline taeniasis prevalence across northern Lao PDR at 8.4% (95% CI = 6.9–9.9%) [30, 32, 33]. Food insecurity can also further exacerbate risk of infection, as pigs known to be infected are sold at reduced prices, and cystic meat may not be discarded by a household under food pressures [31, 32]. In addition, Bardosh et al. [32] demonstrated through Laos-based ethnography and participant observation that cystic pork was sometimes consumed unintentionally, as intermittent access to sources of electricity made it difficult to identify and adequately cook cystic meat during food preparation.

Fertilised *T. solium* eggs can result in further disease if ingested by humans, resulting in human cysticercosis [31]. Human ingestion of *T. solium* eggs occurs via the faecal to oral route, either through environmental exposure to eggs or as a result of autoinfection. Once the outer layers of egg have been digested, the larvae of *T. solium* can bore through the human gut and encyst in the bodily tissues, as occurs in pigs [30]. *T. solium* larvae can invade a variety of human tissues, commonly including the nervous system, a condition known as "neurocysticercosis" [30, 32]. Neurocysticercosis following ingestion of *T. solium* eggs is one of the most severe clinical outcomes of *T. solium* infection and is a leading cause of preventable epilepsy in developing contexts [30–32]. In the case of *T. asiatica*, while there is some speculation in the literature, it has not been definitively proven to lead to cysticercosis [30, 31].

Although Southeast Asia is considered endemic for porcine cysticercosis, taeniasis and human cysticercosis may not be endemic to Vietnam specifically [31, 35]. Few recent studies have assessed the illness burden of human taeniasis and cysticercosis in Vietnam, and there is no wholly reliable estimate of its prevalence [36]. Given the role of inadequate sanitation in the transmission of *Taenia* spp., it would be less likely for cysticercosis to occur in developed areas with adequate sanitation. Rather, it is reasonable to suggest that *T. solium* may be concentrated in regional and underdeveloped areas. Northern provinces of Vietnam that border established hyperendemic areas of Lao PDR would be particularly at risk, as people either side of the border share similar environments, trade pigs, and engage in raw pork consumption [32]. Infection rates may also be gendered, with research from Lao PDR, indicating that cysticercosis is more frequently observed in men than in women [30]. This gendered distribution may be a reflection of socialised taste preferences, with Bardosh et al. [32] reporting that male interviewees were more likely to consume raw meat in line with cultural connotations of masculinity and strength.

3.2.2. Trichinella spp. *Trichinella* species are intracellular intestinal parasites that can infect domestic pigs and wild animals. Ingested larvae mature and mate in the lumen of the gastrointestinal tract, with females then invading the epithelial cells of the host's intestinal lining to produce larvae [37]. Larvae travel from the epithelial cells of the small intestine via the host lymphatic to the circulatory system, where they are then deposited into striated muscle cells [38]. Once in the striated muscle, the larvae develop a cystic capsule and redirect host resources the capsule in order to facilitate survival [38]. Adult worms are excreted by the host when they die, thus consumption of larvae in the host tissue by a new host is required to complete the lifecycle [38]. There are three species of *Trichinella* that are pathogenic to humans, though *Trichinella spiralis* is the most commonly found in domesticated pigs and the species most associated with foodborne disease [37].

Clinical symptoms of "trichinellosis" vary across the different stages of the parasites' lifecycle. As females invade the epithelial cells of the small intestine, human hosts may be asymptomatic or present with mild gastrointestinal symptoms such as diarrhea and abdominal pain [37, 38]. As trichinellosis progresses from the intestinal phase through to the muscular phase, larvae that encyst in striated muscle elicit symptoms including muscle pain and inflammation, fatigue, fever, facial oedema, and nausea [38]. A heavy parasitic load, or resulting secondary infections, can result in severe conditions including pneumonia, myocarditis,

encephalitis, and adrenal gland failure [34, 38]. Respiratory failure can also occur if the larvae invade the diaphragm or intercostal muscles [38]. As such, timely administration of antihelminthics is crucial for patients with a high parasitic load in order to prevent death [37].

Epidemiological data on trichinellosis cases in Vietnam is limited, and it is likely that many cases go undiagnosed or misdiagnosed [38]. Five outbreaks infecting between 20 and 36 people each were documented in Vietnam between 1970 and 2012, all of which followed large social gatherings including weddings and Lunar New Year celebrations [37, 39]. In the most recently recorded outbreak, occurring in 2012, patients experienced symptoms including fever, muscle tenderness, oedema, difficulty swallowing, laboured breathing, and difficulty moving within 5–8 days of raw pork consumption [39]. During documented outbreaks, multiple patients with trichinellosis had also been misdiagnosed as having leptospirosis in the initial stages, a bacterial infection common in Vietnam with similar clinical presentation [37]. These cases of misdiagnosis were corrected upon transfer to urban or speciality hospitals. Yet, these cases indicate that a number of trichinellosis illnesses or deaths in Vietnam may be misattributed to leptospirosis. It is reasonable to suggest that other outbreaks likely occur in Vietnam, though outbreaks with fewer patients or milder symptoms may escape the attention of health authorities altogether [37].

The existing literature indicates a number of risk factors that underscore the epidemiology of trichinellosis in Vietnam. In Vietnam, trichinellosis predominantly affects people in the northern mountainous regions that border Lao PDR and China [37, 38]. These regions are at increased risk of *T. spiralis* infection as domestic pigs commonly roam freely, where they may encounter and consume the carcass of other *T. spiralis* hosts including rodents, dogs, cats, and other pigs [37]. However, human infection is also strongly associated with consumption of raw, undercooked, or fermented meat products [34, 37, 38]. Compared to other outbreaks documented around the world, documented outbreaks in Vietnam are relatively severe with a higher mortality rate, indicating a large number of viable larvae consumed [37]. With estimates that up to 85% of trichinellosis cases in Vietnam occur in men, the illness burden is also gendered [38].

3.3. Antibiotic Residues. In addition to promoting antibiotic resistance in zoonotic pathogens, which makes human infections more difficult to treat, widespread antibiotic use in livestock also impacts human health through the oral consumption of residues in meat products. In Vietnam, many farmers have turned to antibiotic use in order to mitigate epidemics, minimise stock loss, and maximise profits [40]. As such, alongside administration for their acute therapeutic value, antibiotics are also used as a prophylactic measure and for growth-promotion effects [41]. Often, antibiotics are administered through feed and without veterinary supervision, so the dosage of antibiotic administered may not align with manufacturers' recommendations [41]. When a high dose is delivered to livestock, residues of the antibiotic can be detected in meat being sold for human consumption. This is particularly the case when withdrawal periods, a waiting period after antibiotic use to ensure it is eliminated from animal before slaughter, are not observed [42]. The threat that antibiotic residues pose to human health is twofold, with the more acute risk being that residues above certain levels can be toxic to humans [42]. However, even at low levels that are non-toxic, there is concern that long-term, low-level antibiotic exposure may alter the human microbiota and contribute to the development of chronic health conditions [42].

The Vietnamese government has taken steps to curb potentially harmful use of antibiotics in agriculture though regulation and surveillance remain difficult to enforce. In 2007, Vietnam joined the World Trade Organization and henceforth was obliged to adhere to its list antibiotics that are banned for use in livestock production [40]. Since joining, the Ministry of Agriculture and Rural Development has updated guidelines pertaining to the sale and use of prohibited drugs [40]. However, the proportion of smallholder pig producers in Vietnam makes monitoring the use of antibiotics in livestock difficult to achieve, particularly as most meat is sold at informal or traditional markets [40]. Further barriers to domestic testing and surveillance systems in Vietnam include the costs associated with testing the amount of pork produced nationally, as well as for the number of different antibiotics utilised by agriculture [7]. As a result, surveillance efforts have been more successful at maintaining the quality of products destined export, which are sold through formal channels and must meet safety regulations imposed by importers [5].

Available research has demonstrated that both legal and illegal antibiotic residues remain a problem for Vietnamese pork products. Two legal and widely used antibiotics used in pig production, tetracycline and fluoroquinolones, have had contrary results in the research. One major study found virtually no tetracycline and fluoroquinolone residue in pork meat products [41]. However, a 2013 study from the Red River Delta region found that 39% of pork samples collected from markets were positive for tetracycline or quinoline residues, or both [40]. Testing has also uncovered the use of banned drugs including chloramphenicol in pork production [41]. Low levels of beta-agonists, antibiotics classed as illegal growth promoters, have also been found [41].

Of the many antibiotic residues tested for across Vietnamese studies, residues from legal sulphonamides appear to be the most commonly found in pork. In one study of meat samples from central and southern Vietnam, which tested for residues of 21 different antimicrobials, 8.8% of pork meat samples were positive for sulfamethazine [8]. In this study, none of the other 20 antimicrobials being tested for were detected [8]. Another study testing pork meat from Ho Chi Minh City had similar results, with sulfamethazine residues (11–1600 μg/kg) found in 23% of samples, with none of the other 27 residues chosen for inclusion in the study detected [43]. Further, a quantitative and qualitative study of sulfamethazine levels in pork meat found that 11% of pork samples tested were positive with sulfamethazine above maximum residue limits [41]. However, more research will need to be undertaken to ascertain the full extent and impact of legal and illegal antibiotic use in livestock in Vietnam [41].

3.4. Heavy Metals. In the 2015 report on global foodborne illness, the WHO did not explore illness resulting from heavy metal exposure, citing that robust methods to estimate disease as a result of metals such as lead and cadmium do not currently exist [2]. To date, one study has examined heavy metals in pork liver, kidney, muscle, and pig feed in Vietnam. Lead was found in 11.1% of feed samples, 55.6% of liver samples, 38.9% of kidney samples, and 27.8% of muscle meat [41]. Cadmium was found in 94.4% of feed samples, 100% of liver samples, 100% of kidney samples, and 0% of muscle meat [41]. Arsenic was not found across any of the feed, liver, kidney, or muscle meat samples [41]. For both lead and cadmium, the levels detected were below maximum residue levels. However, further research will be required to adequately comment on the heavy metal contamination of pork products in Vietnam and any associated health consequences.

4. Conclusion

This review demonstrates the scope and complexity of risks that pork can present to consumers in Vietnam, though there are notable absences of some known risks in the published literature. Chemical risks in Vietnamese pork products are particularly hard to deduce, with only one major study assessing heavy metal contamination and few studies attempting to capture the mosaic of antibiotic residue contaminants. Biological hazards associated with Vietnamese pork products, specifically bacteria and parasites, have been more closely studied and definitively attributed to disease outcomes and mortality. Still, *Salmonella* spp., *S. suis*, *T. solium*, and *T. spiralis* do not represent the full scope of known pathogens associated with pork consumption. The omission of other appropriate pathogens from this review is a result of gaps in the available research specific to Vietnam and comparable countries of Southeast Asia. Other pathogens known to colonise pigs and infect humans following pork consumption (including Hepatitis E, *Staphylococcus aureus*, and *Campylobacter jejuni)* are virtually absent from relevant literature. Little research to assess the impacts of pathogenic *Escherichia coli* consumed through pork products results in another notable gap in the literature, with most studies focused on antibiotic resistance harboured by different pork-borne *E. coli* isolates. However, a limitation of this review is that only articles published in the English language were considered for inclusion. The aforementioned gaps may be less significant in Vietnamese language literature, or in literature written in other languages of Southeast Asia.

Pork-associated pathogens that are more comprehensively discussed by the literature and detailed in this review illustrate the presence and impacts of gradients of development in Vietnam. For instance, disease as a result of parasitic infection is more frequently documented in regional areas of Vietnam, where populations have lower relative levels of sanitation infrastructure, reduced access to healthcare, and where livestock may be permitted to roam in order to graze [37]. Falling under the umbrella of neglected tropical diseases, *T. solium* infection is associated with lower relative levels of socioeconomic development in affected areas. However, alongside pathogens that are more prevalent in low-income countries, Vietnam also has burgeoning food processing and chain retail sectors, where larger slaughterhouses and additional handling processing can facilitate cross-contamination of *Salmonella* bacteria between products. Ubiquitous in pig farming and slaughterhouse environments, high-income countries with developed food safety protocols, and surveillance systems have yet to eliminate foodborne salmonellosis [2]. Thus, any attempts to address food safety in Vietnam must capture this complex, yet rapidly evolving food landscape.

Review of the literature suggests that an effective way to curb the incidence of foodborne illness in Vietnam would be through public health interventions that successfully reduce the consumption of raw pork. Application of sufficient heat to pork products during the cooking process is crucial to reducing the load of viable organisms on or within the meat. A multitude of studies included in this review implicated raw pork consumption as a prominent risk factor in the development of disease from biological pathogens [23–25, 29, 30, 32–34, 37, 38]. However, epidemiological trends indicate that raw or undercooked pork dishes are part of prominent sociocultural events such as celebrations and funerals [24, 32, 33, 37, 39]. The cultural significance of raw pork consumption appears particularly prominent in mountainous areas of northwest Vietnam that border Lao PDR, which have been the site of multiple recorded outbreaks of pork-borne parasites [30, 32, 33, 39]. Thus, despite Takeuchi et al. [29] reporting some initial success using an educational intervention in Thailand, other authors have critiqued reliance on educational or biomedical paradigms in this respect [32]. Bardosh et al. [32] argue that transdisciplinary valuations of cultural and structural factors surrounding raw pork consumption are required to adequately engage with the issue.

Finally, the epidemiological data explored across the foodborne pathogens included in this study reflected relatively consistent patient demographics. Various studies have reported that males are affected by pork-related foodborne illness at a significantly higher rate than females across Southeast Asia [23–25, 30, 38]. Age was also positively associated with infection and disease following pork consumption in some studies [23, 25, 30]. Thus, if raw pork consumption is a result of socialised tastes, it may be changing with younger generations of Vietnamese consumers, predominantly remaining amongst older generations of Vietnamese men. However, trends in the gender and age of patients may be a reflection of other underlying risk factors, such as lifestyle behaviours, health comorbidities, or age-associated immunodeficiency. As such, further research to determine why these demographic patterns are repeatedly observed could help underscore disease prevention efforts.

Disclosure

This work was completed as part of ongoing research conducted by the Center for Public Health and Ecosystem Research, Hanoi University of Public Health.

Conflicts of Interest

The authors have no conflicts of interest or financial interest to disclose.

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