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Integrating market chain assessments with zoonoses risk analysis in two cross-border pig value chains in Lao PDR

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Objective: Lao PDR's recent accession to the World Trade Organization necessitates a greater understanding of the patterns and risk of livestock production in order to better align national policy with the Agreement on the Application of Sanitary and Phytosanitary Measures. This eco-health study was conducted to improve understanding of the interrelations between market chains and zoonotic infection risks at two strategic cross border points between Lao PDR, Thailand and Viet Nam.
Methods: Information gained from smallholder farmer/trader interviews was integrated with serological surveys for pig-associated zoonoses—including hepatitis E virus (HEV), *Taenia solium* (*T. solium*) and *trichinella*—to identify potential linkages between disease risk and pig production and slaughter in low input systems common across the country.
Results: *Trichinella* and HEV exposure was high in both humans and pigs in both study areas, significantly associated with pig slaughter and the subsequent consumption and handling of raw pork products. *T. solium* demonstrated a strong geographical and ethnic association with the northern study area bordering Vietnam. With the right knowledge and accessible, affordable inputs, the majority of smallholder farmers indicated a willingness to invest more in pig production, which could simultaneously improve livelihoods and decrease exposure to HEV, *Trichinella*, and *T. solium* through increased access to formal markets and an improved slaughter processes.
Conclusion: The linkages identified when assessing disease risk in the context of potential economic and cultural drivers of transmission highlight the importance of a systems-based approach for the detection and control of zoonotic disease, and contributes to an improved understanding of the Lao PDR livestock sector.

Keywords: Systems Approach; Public Health; Value Chain; Community Development; South East Asia; Eco-health

INTRODUCTION

Livestock movement pathways in Southeast Asia's Greater Mekong Sub-region (GMS) are highly dynamic, with significant changes in livestock volume and direction occurring in relatively short periods of time. Despite recent improvements in transnational dialogue to manage and strengthen GMS cross-border trade issues [1], the generally poor management of livestock disease by smallholder farmers, coupled with the fact that many cross border pathways remain unrecognised by country officials, remains an ongoing challenge to regional biosecurity [2,3].

Bordered by five countries in the GMS, Lao PDR is both an importer and significant 'transit country' for livestock such as cattle, buffalo and pigs moving between larger markets in Thailand, China and Vietnam [4]. Strong market-pull from neighbouring Vietnam and China provides unprecedented opportunities for local pig production in this small country, however despite recent increases, local pork production still remains insufficient for larger population centres such as Vientiane and Luang Prabang. For example, an estimated 40% of pigs consumed in Luang Prabang province are from Xayaboury province, often originating in Thailand [3]. Despite 25 official border control points, the porous nature of Lao PDR's borders—many of which consist of overland tracks in mountainous regions that have been used for generations—has the potential to negatively impact on the livestock disease control and risk management in the country.

The 2013 accession of Lao PDR to the World Trade Organisation (WTO) necessitates enhanced compliance with the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement); the driving framework for international requirements regarding the protection of animal, human and plant health [5]. Despite a number of positive steps—including establishment of the Lao PDR Trade Portal and revision of trade-related legislation [6]—there remains a requirement for greater risk-based management of unsafe food items derived from animal products [7]. The research reported here implements a transdisciplinary approach to better understand the risks of porcine foodborne zoonoses such as *trichinella*, *Taenia solium* (*T. solium*), and hepatitis E virus (HEV), which have been identified in earlier studies as problematic [8-10] in the context of current and potential future market chains and smallholder farmer behaviour.

MATERIALS AND METHODS

Study site selection

The study was undertaken in pork value chains at two Lao PDR cross border sites; Xayaboury district in Xayaboury Province on the western Lao-Thai border, and Mai District bordering Vietnam in the northernmost Phongsaly Province. Xayaboury district encompasses 77 villages (approximately 70,000 people) around the provincial capital of Xayaboury province [11]. It is bordered by Hongsa district in the north, Phiang and Pak Lai districts in the south, Vientiane province to the east and northern Thailand to the west (Figure 1). Mai District is located in the south-east of Phongsaly province, sharing borders with Khua district to the south-west, Ngoy district (Huaphan province) to the south, Samphan district to the north-west and the Vietnamese province of Dien Bien to the north and east (Figure 1). Of the 88 district villages, only half are accessible by road, with the total district population of 25,448 dispersed over 4,365 households [11].

District selection considered a number of factors including local government support, evidence of increasing smallholder pig production and improved market access, as determined through consultation with both local farmers and external stakeholders. Moreover, a review of research into key pig-associated zoonoses in Lao PDR over the last 25 years found no prevalence data was available in these districts [12]. Once districts had been identified, eight villages were selected based upon essential criteria including

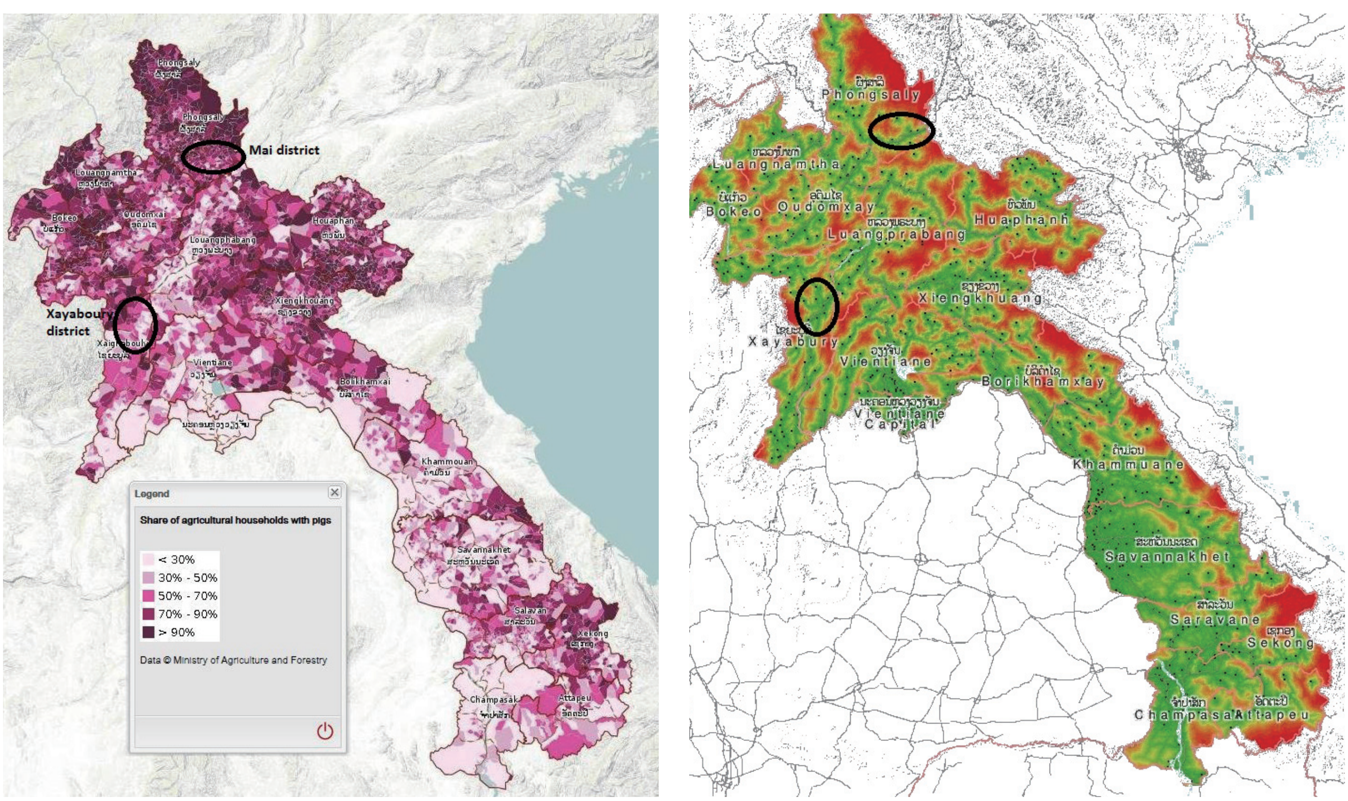

Figure 1. Location of intervention sites, **left** pig density per district (2011), **right** access to basic health facilities (access varies between >1 h→10 h travel time) (2005) (taken from [32]).

accessibility, high district pig numbers, areas of high poverty and broad ethnic diversity (Table 1).

Market chain study

The market chain study largely followed the methodology described by Wandschneider et al [13]. Once study locations were identified, local government representatives facilitated the rapid market appraisal consisting of combination research methodologies including qualitative participatory appraisal and quantitative surveys. Focus group discussions conducted with village participants and traders aimed to i) understand the motivations and constraints for smallholder pig production and trade, ii) track pig movements along the market chain, and iii) identify potential future access to profitable markets. Structured questionnaires were administered to a total of 66 farmers, 14 traders and the eight village heads in order to collect quantitative data on household characteristics, pig production systems and constraints, and marketing practises.

Serological survey and risk factor analysis

Alongside the market chain analysis, a cross sectional serological survey was undertaken in both pigs and humans to determine the point prevalence of six key pig-associated zoonoses (Japanese encephalitis [JE] virus, *T. solium* [14], *trichinella*, 20HEV [15], *Coxiella burnetii*, and brucellosis [9]), and the transboundary animal diseases (TADs) classical swine fever (CSF) and porcine respiratory and reproductive syndrome (PRRS). Risk factor questionnaires were administered to a representative from each participating household.

The human sampling frame was determined through a probability proportional to human population design according to the most recent national census (2005). The sample size calculation [16] used an estimated disease prevalence of 50% to determine human prevalence with 80% power and 5% precision. A total of 128 people (78 females, 50 males) were randomly selected to provide sera samples across the eight villages, representing 3.0% of the total target population. Unlike the human population, the village pig populations could not be determined with any certainty, however prior scoping studies demonstrated approximately 90% of households in each village owned pigs. It was therefore assumed that villages with larger human populations would likely have similarly large pig populations, resulting in the number of pigs randomly sampled per village being matched to the number of people sampled (n = 128). Researchers conceded that this approach would result in lower precision compared to the human survey, although results would still indicate whether the burden of disease was low, moderate or high. Pigs were randomly selected from households that owned pigs of eligible criteria (greater than 4 weeks old, not near-full term pregnancy). Blood samples for both pigs and humans were collected in plain vacutainers and serum extracted for analysis. Samples were refrigerated and then placed on ice until arrival at the human and animal health laboratories, where they were frozen at –20°C before analysis. Pig and human sera were analysed in Vientiane at the Lao PDR National Animal Health Laboratory (NAHL) and the National Centre for Laboratory and Epidemiology (NCLE), respectively.

Table 1. General characteristics of the eight study villages

Village	Distance from district centre (km)	Represented ethnicities	Number of people in village
Xayaboury			
A	18	Khmu/Lao	1,115
B	16	Khmu/Hmong	905
C	15	Hmong	275
D	10	Hmong/Lao/Mian	812
Phongsaly			
E	18	Tai Dam	372
F	15	Khmu	147
G	11	Tai Deng/Khmu/Tai Dam	528
H	6	Khmu/Tai Dam	247

Human sera were tested for the presence of antibodies against hepatitis E (HEV enzyme-linked immunosorbent assay (ELISA) 4.0, MP Diagnostics Singapore), *Trichinella* (*T. spiralis* IgG ELISA, IBL International, Hamburg, Germany), JE and JE:dengue antibody ratio (JE-dengue IgM Combo ELISA Test E-JED01C, Panbio, Brisbane, Australia), *Taenia solium* taeniasis and cysticercosis (EITB test kit, CDC, Atlanta, GA, USA), brucellosis (non-commercial ELISA, Australian Animal Health Laboratory [AAHL], Geelong, Australia) and *C. burnetii* (FQS-MS-2P-664 IDVET, Grabels, France). Pig sera were tested for presence of antibodies against hepatitis E (HEV ELISA 4.0v kit, MP Diagnostics Singapore), *Trichinella* (Priocheck Trichinella Ab ELISA, Prionics, Schlieren, Switzerland), JE IgM (non-commercial ELISA, AAHL, Australia), brucellosis (non-commercial ELISA, AAHL, Australia) *C. burnetii* (FQS-MS-2P-664 IDVET, Grabels, France), PRRS (PRRSX3 Antibody Test IDEXX Laboratories, Westbrook, ME, USA) and CSF (PrioCHECK CSFV 2.0 Prionics, Lelystad, Netherlands). All questionnaire and serological data was stored in a secure database.

Questionnaire and laboratory data were entered into a spreadsheet (Excel; Microsoft, Redmond, WA, USA) and analysed using the SPSS software (IBM, USA version 16.0, New York, NY, USA). Initial exploratory data analysis was performed using multiple correspondence analysis (MCA), after which cross tabulation and Chi-Square tests were used to determine significant associations between serological results and variables such as gender, ethnicity, pig production and consumption habits. The conventional asymptotic significance (p) level of 0.05 was subsequently used to determine the level of significance between the variables, with odds ratios (OR) used to estimate the risk within a 95% confidence interval.

Ethical clearance

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Lao

PDR National Ethics Committee for Health Research (NECHR, permit number 772) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All applicable institutional and/or national guidelines for the care and use of animals were followed. Informed consent was obtained from all individual participants included in the study.

RESULTS

Village dynamics and pork production systems

The Xayaboury district villages had over twice the average human population compared to Mai district villages (Table 2), reflecting the smaller, more remote populations found at higher elevations in the far north of the country. The two districts were also represented by different ethnic groups; whilst Khmu were found in both districts, the Xayaboury district villages additionally consisted of Hmong and Lao ethnicities, whilst ethnic minority groups such as the Tai Dam and Tai Deng were represented in the northern Mai district villages only (Table 1). The generally higher levels of poverty detected in the Mai district cluster—determined by indicators such as education level, access to basic sanitation and the number of government-assessed poor households (Table 2)—aligns with current assessments identifying Phongsaly province as one of the lesser developed in the country [11].

Villages demonstrated a diverse range of smallholder business models. Pig-rearing was a valuable cashable asset in addition to rice cultivation, with the majority of pigs raised in low-input systems (1 to 15 pigs per household). Even where pigs were considered the primary income generator, specialized production and marketing systems were lacking, with opportunistic sales common (Table 2). At the time of survey, 68% farmers felt pig disease to be a major limitation to optimising production levels, with 13.8% and 21.1% of respondents in Mai and Xayaboury districts, respectively, reporting sudden pig deaths in the last 12 months. Conversely, only 11% demonstrating increased pig numbers in recent years, largely as a result of improved market opportunities. Despite the numbers kept, the time afforded to the pig enterprise also highlighted the low input systems in the two target areas, with pig care comprising less than one hour of the daily activities for over 50% of respondents (Table 2). The majority of this time was spent in feed preparation, commonly rice bran, cassava roots, maize, taro (*Colocasia* species) and banana stems; the use of concentrated commercial feeds was absent.

Whilst over 95% of farmers in both districts penned their

Table 2. Descriptive statistics for key health and pig production parameters for the two village clusters

Parameter	Phongsaly province	Xayaboury province
Household characteristics		
Average village population	312.3 (147-528)	776.8 (275-1115)
Mean number of households	55.5	98.3
Mean household size	6.6	6.5
Total households with toilets (% respondents)	38.3	82.2
Education level (% respondents)		
No schooling	22.8	12.9
Primary	61.4	60.0
Secondary	15.8	25.7
Tertiary	0.0	1.4
Human health		
People who consumed pork in the last one month (% respondents)	19.3	25.4
Pig production		
Reason for keeping pigs (% respondents)		
Sell piglets	29.3	56.3
Fatten pigs	53.4	23.9
Ceremonial sacrifices	34.5	9.9
Opportunistic income	50.0	47.9
Production systems (% respondents)		
Free range-wet season	3.4	1.4
Free range-dry season	37.9	11.3
Never penning pigs	41.3	12.7
Disposal of pig faeces (% respondents)		
Into water supply	32.8	26.8
Into food supply	31.0	15.5
Time input into pig production per day (% respondents)		
0-1 h	52.6	70.0
2-3 h	28.1	17.1
Over 3 h	19.3	12.9
Number of respondents that have experienced sudden death of pigs in their farms (in %)	13.8	21.1

pigs during the wet season to prevent crop damage, only 11.3% of farmers in Xayaboury district let their pigs range freely during the dry season, compared to 37.9% in Mai district. Pens were often built next to streams, in order to facilitate access to water for consumption and cleaning. Around 30% of Mai district respondents disposed of penned pig faeces in food and water supplies, with 26.8% and 15.5% of Xayaboury district farmers disposing of it in food and water sources respectively (Table 2). Pigs were predominantly kept within the village boundaries, although during the wet season animals could be moved to an isolated area outside the village known as a sanaam. Despite over 75% of farmers indicating their pigs mixed with others at some point in the year (Table 2), animal health inputs such as anthelmintics and vaccination were rarely used. Quarantine practises (understood by respondents as a temporary physical separation of new and existing pigs) also appeared poor in all villages, with less than 10% of farmers indicating new pigs were quarantined. In-breeding was common in both districts, with boars generally coming from the same village—if not the same litter—as the sows. Farmers perceived the main constraints to improved pig production to be disease, lack of feed and lack of labour in this order, with 25% of interviewed farmers reporting insufficient knowledge of how to address the relevant problems, wishing to have better access to information. Despite this, over 50% of farmers were interested in improving their pig enterprises—both piglet production and pig fattening—to obtain more income.

Pig sales, trade and slaughter patterns

All farmers sold their pigs to brokers or traders who visited the villages on average 3 to 4 times per month. Traders transported between 2 to 4 animals via motorbike, increasing to 10 to 20 head where vehicle access was possible. Farmers had no clear idea about trader preferences in terms of size and breed, however felt that local breeds (Moo Lat) were generally preferred over exotic breeds due to their higher fat:muscle ratio.

The majority of farmers reported selling 0 to 5 pigs in the previous 12 months, with around 25% selling 6 to 10 animals and a small proportion selling over 15, reflecting several piglet fattening enterprises in Xayaboury district. Farmers reported little negotiating power and inconsistent pricing patterns for pig sales; in some cases pigs were sold for a per head lump sum, in others farmers received a price per kilogram (kg). Pigs weighing 50 to 60 kg generally obtained the best overall prices, while animals greater than 90 kg fetched the lowest prices due to their higher fat content. Bargaining, although practised by some farmers, did not appear to result in significantly better prices, given that farmers generally had no means by which to determine the weight of their animals.

Traders tended to work alone in Xayaboury district, whilst in Mai district they operated in groups; traders in both districts reported engaging in simultaneous business such as guesthouse operation, car service or whiskey production. Traders normally worked within the provincial and district borders due to administrative constraints, although those in Mai district reported some live pig trade occurred across the Sophoun border into Vietnam. Traders perceived pig disease, price competition from other traders, lack of slaughter facilities and insufficient liquidity of retailers as the most common constraints to optimal purchase power. Pigs were sourced by a number of methods including asking around, farmer requests for pick-up, collection through village brokers, or drop-off at the trader's home. Whilst pig availability was not cited as a problem in Mai district, pig supply in Xayaboury district was competitive, particularly during the May-October wet season where poor infrastructure and sanaam usage meant fewer pigs were available for purchase by traders.

Home slaughter and the associated handling of raw pork was common for both traders and the majority of interviewed households, with 94.4% of respondents in Xayaboury district, and 78.9% in Mai district reported slaughtering a pig or handling raw pork products in the previous 12 months. In addition, 25.3% (Xayaboury) and 19.3% (Mai) residents reported consuming raw pork products at least once a month (Table 2). Traders indicated that purchased pigs were generally slaughtered at home and the carcass sold directly at the district wet market; the use of slaughter points was an exception.

Disease seroprevalence in human and pig populations

Trichinella and HEV were identified as key human disease concerns in both provinces, with prevalence of 58.6% (95% confidence interval (CI) 49.9 to 66.8) and 65.6% (95% CI 57.1 to 73.3) respectively (Figure 1). *T. solium* was the only disease that demonstrated a geographically distinct distribution, with human taeniasis (4.7%, 95% CI 2.2 to 9.9) and cysticercosis (9.4%, 95% CI 5.5 to 15.7) prevalence occurring solely in the northern Mai district. The JE, *C. burnetii*, and brucellosis prevalence were 3.1% (95% CI 1.2 to 7.8), 1.6% (95% CI 0.4 to 5.5), and 0.8% (95% CI 0.1 to 4.3), respectively.

Disease prevalence in the pig populations generally mirrored the human results (Figure 2), with high evidence of *trichinella* (23.4%, CI 16.9 to 31.5) and HEV (76.6%, CI 68.5 to 83.1) across both districts. Porcine JE was only detected in Xayaboury district, averaging 4.7% (95% CI 2.2 to 9.9). Porcine *C. burnetii* was detected in 1 village in each district, with an average prevalence of 1.6% (95% CI 0.4 to 5.5). Porcine brucellosis was found in only a single pig in Xayaboury district, resulting in an estimated average prevalence of 0.8% (95% CI 0.1 to 4.3) across the study area. Average CSF and PRRS prevalences of 1.6% (95% CI 0.4 to 5.5) and 7.0% (95% CI 3.7 to 12.8), respectively, were detected across both provinces.

Significant risk factors for zoonoses transfer between pigs and humans

Ethnicity was identified as a significant risk factor for human *trichinella* infection, with both the Tai Deng ($p = 0.005$; OR 5.7,

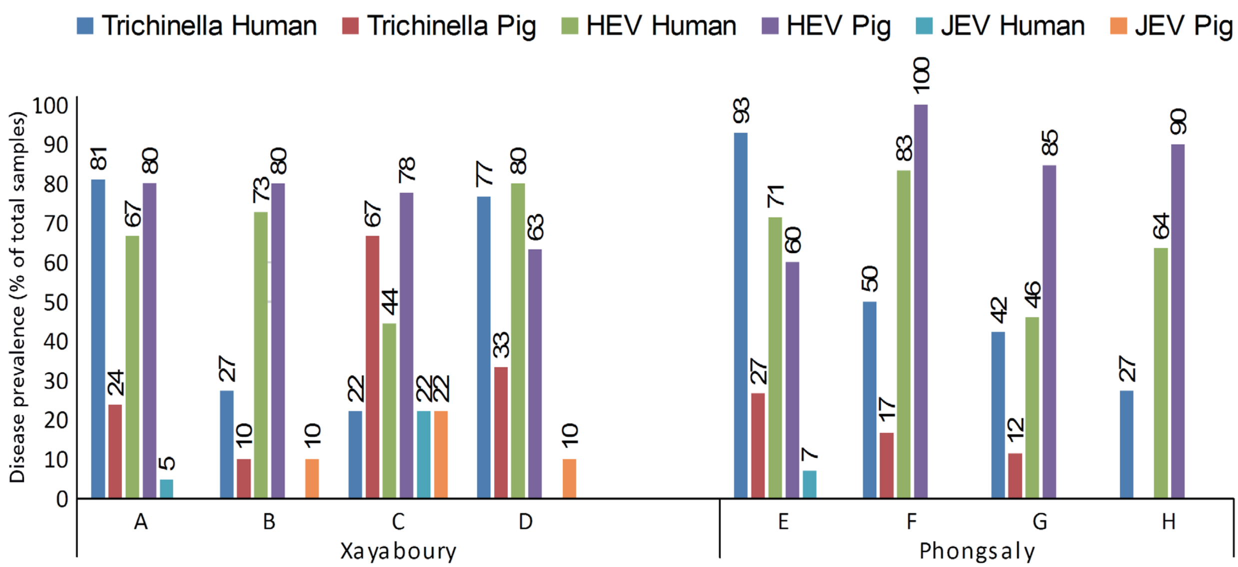

Figure 2. Disease prevalence (% of total samples): Selection of the most important Human and Pig Serological Samples analysed in both provinces.

95% CI 1.5 to 21.7) and Lao Loum (p = 0.006; OR 1.8, 95% CI 1.5 to 2.1) more at-risk compared to other ethnic groups. Ethnicities at greater risk of contracting HEV were the Tai Deng (p = 0.004; OR 5.3, 95% CI 1.5 to 20.0) and Khmu (p = 0.05; OR 2.2, 95% CI 1.0 to 5.2). The Tai Dam ethnicity was significantly at-risk for *T. solium* cysticercosis (p≤0.0005; OR 86.3, 95% CI 10.3 to 724.1) and taeniasis (p≤0.0005; OR 1.3, 95% CI 1.1 to 1.7), with the Khmu (p = 0.044; OR 0.2, 95% CI 0.0 to 1.2) and the Hmong (p = 0.025; OR 0.9, 95% CI 0.8 to 0.9) significantly at-risk for *T. solium* cysticercosis only. The absence of a toilet was also a significant risk factor for both *T. solium* cysticercosis (p = 0.003; OR 5.9, 95% CI 1.7 to 21.9) and taeniasis (p = 0.003; OR 13.9, 95% CI 1.6 to 125.0).

Trichinella was significantly associated with the consumption of raw pork sausage (p = 0.026; OR 3.5, 95% CI 1.1 to 11.2), raw pig blood (p = 0.036; OR 3.8, 95% CI 1.0 to 13.8), and handling of raw pork products (p = 0.033; OR 2.9, 95% CI 1.0 to 8.0). Pig slaughter was a risk factor for HEV (p = 0.02; OR 2.5 95% CI 1.2 to 5.3), *T. solium* cysticercosis (p = 0.034; OR 4.8, 95% CI 1.0 to 22.6) and *T. solium* taeniasis (p = 0.02; OR 1.1, 95% CI 1.0 to 1.2).

DISCUSSION

This study identified several differences in the management and motivation for smallholder pig enterprises between the two provinces. For example, farmers in Xayaboury district indicated a higher propensity for rearing pigs for economic purposes—particularly the sale of piglets (Table 1). This could be for a number of reasons, for example a result of better established market chains feeding in from Thailand towards Luang Prabang in this area [3], the propensity for Hmong to rear piglets for sale [17] or the improved infrastructure and generally lower poverty levels compared to the north (Table 1 [11]). Mai district farmers were instead more likely to keep pigs for fattening and ceremonial purposes (Table 2), the latter in particular aligning with traditional cultural beliefs of the Tai Dam and Tai Deng ethnic groups. However these apparently small differences can have strong implications in terms of disease risk for both pigs and humans. For example, the significant correlations between ethnicity, *trichinella* infection and the consumption of raw pork products identified in this study (Table 3) aligns with previous reports of *trichinella* outbreaks in northern Lao PDR and Vietnam as a result of ceremonial consumption of raw pork [18-20]. *T. solium* infection has also been linked to ethnic practises in the north of the country [21]. Overall, a stronger focus of pig raising for ceremonial slaughter and consumption may correspond to greater intra-community circulation of foodborne

Table 3. Significant risk factors

Disease	Risk factor	Odds ratio	CI	p-value
Trichinella	Ethnicity – Tai Deng	5.7	1.5-21.7	0.005
	Ethnicity – Lao Loum	1.8	1.5-2.1	0.006
	Eating raw sausage	3.5	1.1-11.2	0.026
	Drinking raw blood	3.8	1.0-13.8	0.036
	Handling raw pork	2.9	1.1-8.0	0.033
Hepatitis E	Ethnicity – Tai Deng	5.3	1.5-20.0	0.004
	Ethnicity – Khmu	2.2	1.0-5.2	0.054
	Slaughtering pigs	2.5	1.2-5.3	0.017
Taenia solium cysticercosis	Ethnicity – Tai Dam	86.3	10.3-724.1	0.000
	Ethnicity - Khmu	0.2	0.0-1.2	0.044
	Ethnicity - Hmong	0.9	0.8-0.9	0.025
	No Toilet access	5.9	1.7-21.3	0.003
	Slaughtering pigs	4.8	1.0-22.6	0.034
Taenia solium taeniasis	Ethnicity – Tai Dam	1.3	1.1-1.7	0.000
	No Toilet Access	13.9	1.6-125.0	0.003
	Slaughtering pig	1.1	1.0-1.2	0.021

zoonoses such as *trichinella* and HEV, whereas sales-oriented pig production could better facilitate the spread of both TADs and viral zoonoses [22] across broader geographical areas, highlighting the importance of understanding the motivations, purpose and methods for pig keeping when identifying potential high disease risk areas.

It has been shown that changes in agricultural systems, especially transitions towards more intensified farming, opens new routes for the emergence of zoonotic diseases [23]. This can be prevented through the appropriate farm-level investment in pig production, but evidence from this study aligns with previous findings (for example [24]) that economically disadvantaged households tend to invest less in pig health and feed inputs. For example, the feeding of concentrates was absent, and serological assessment confirmed market chain findings that pig vaccination periodically occurred in only one village (Xayaboury district). A worrying 68% of farmers reported pig disease and the associated poor growth rates to be a limiting factor to improved production, with a further 25% indicating they lacked sufficient knowledge of how to improve the current systems, in line with other findings [25]. However, the low input production systems described by the farmers in both districts not only negatively impacts on livelihoods; they may also be having an adverse effect on human health in these villages. For example, the widespread practice of free ranging pig production identified in the market chain analysis and a specific larger survey could be a factor in *trichinella* spread, known to be transmitted by the access of free ranging pigs to food scraps [26]. Also interesting to note was that exposure to *T. solium* —transmitted by the access of pigs to human faeces [27]—was confined to the northern Mai district where the market study identified a greater proportion of farmers left their pigs free-ranging all year around (Table 2). *T. solium* was also significantly correlated to a lack of toilets (Table 3); the market analysis identified less than 40% of households in Mai district had access to a latrine compared to over 80% in Xayaboury (Table 2). The fact that around 30% of interviewed farmers dispose of pig faeces in local food or water sources in close proximity to their pig pens (Table 2)—a known risk factor for HEV [28]—could also be contributing to the high HEV prevalence observed in both pigs and humans across both districts. With the right knowledge and accessible, affordable inputs, the majority of farmers indicated they would be willing to invest more in pig production, which could potentially impact the currently high exposure to diseases such as HEV, *trichinella* and *T. solium*. Further investigation into how livestock and extension services can be improved in these areas is warranted from both a socioeconomic and health perspective.

This study also identified several limitations for both producers and traders regarding pig sales in the two districts, with only 11% of interviewed farmers indicating market opportunities for pork had improved in recent years. Poor knowledge of market prices, compounded with a lack of verification tools such as scales to weigh animals, meant that smallholder farmers in these parts of Lao PDR aligned to the observed phenomenon of pig farmers as 'price takers not price makers', with little opportunity to break the low income-high risk cycle associated with smallholder pig production in the region more generally [29]. This lack of opportunity to engage with formal markets also increases the likelihood of zoonotic disease propagation through home slaughter, identified in this study as a significant risk factor for HEV and *T. solium* taeniasis and cysticercosis (Table 3). Furthermore, the associated handling of raw pork, practised by the majority of interviewed traders and producers, was implicated in *trichinella* infection (Table 3). The significant association of risk between pig slaughter and handling of raw pork products with diseases such as HEV, *trichinella* and *T. solium* identified in this study provides further impetus for improved controls of the purchase, processing and sale of pigs and pork products more generally in Lao PDR. Whilst a more formalised trade and slaughter process was deemed desirable in terms of increasing the numbers of pigs that could be sold and processed, meat inspection has long been highlighted as an important mechanism to prevent and control food-borne zoonoses in the Asia region [30]. Given traders also play a central role in the value chain as a link between communities, other traders, slaughterhouses and consumers in the study areas, their behaviour can also significantly influence disease dynamics in their operational areas. For example, the collection of small numbers of animals from various locations and mixing them during transport described here has been identified as a key factor in livestock disease transmission in the GMS more generally [2]. In this way, the lack of access to formal markets not only reduces the potential economic benefits from pig raising enterprises, but also increases public health risk of zoonoses exposure in both producers and traders.

One of the study limitations is a lack of records or existing data that could be used as reference or control for our findings in Lao PDR. Detailed up-to date information about the number of health care facilities per province or district is not publicly available (Figure 1 gives the most recent data), and less so human treatment data [31]. Data on animal healthcare facilities are even more limited, and largely restricted to public services. Future efforts in the strengthening of both human and animal health systems would help establish solid reference data that allow research findings to be supported by available information at a national or regional context.

IMPLICATIONS

Complementing market chain assessments with serological studies and risk analyses for several pig-associated zoonoses provides a better understanding of the selected overall pork value chains from a pig production and public health perspective. We highlight the potential long term positive impact on both human and pig disease through improved market opportunities such as central collection points, increased smallholder negotiation power and greater knowledge of both the economic potential and public health impacts of smallholder pig production. Raising awareness of pig-associated zoonoses in current human health and development programmes could reduce infection risks and contribute to various trade-related activities associated with Lao PDR's accession to the WTO.

CONFLICT OF INTEREST

We certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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