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Swine Industry in Canada: Biosecurity in Live Animal, Semen Transportation, and Embryo Transfer

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Abstract

The pork industry, a key player in the Canadian economy, significantly contributes to livestock production, international trade markets, and employment. The multi-faceted swine industry is comprised of nucleus, multiplier, and commercial herds. The recognition and application of exemplary internal and external biosecurity measures are paramount for maintaining sustainable swine production. Historically, live animal transport has been an important means of disseminating superior genetics between production herds and poses a considerable risk for disease transmission and biosecurity breach points. The industry has evolved over time to employ other methods, through the shipping of boar semen and the adoption of artificial insemination practices to acquire genetic resources with a lower risk of disease transmission. These effective changes have led to an improvement in herd health, production performance, and efficiency. In particular, the industry's dedication to enhanced biosecurity is evident in the effort to streamline embryo collection and transfer procedures. Such advances reduce the potential need to transport live animals, thereby lowering the risk of introducing infectious agents. This review article explores the different forms of disseminating swine genetics, namely, live animal, semen transportation, and embryo transfer, examining potential breaches in biosecurity, and discussing mitigation strategies that reduce disease transmission to protect the health of animal stock.

Keywords: biosecurity; disease transmission; embryo transfer; live animal; semen; swine; transport

1. Introduction

The swine industry is a complex and highly integrated livestock production system that is considered an important sector in both domestic and global markets. The Canadian pork industry is considered the third-largest global exporter of pork products, trading with 94 countries and generating an estimated $4.7 billion (CAD) annual export revenues (AAFC, 2020). In Canada, the domestic market for pork is robust, with an annual consumption of over 15 kg/person/year, consuming approximately 22% of all pork produced (AAFC, 2022; OECD, 2023). In addition to pork consumption, the swine industry is an important economic driver in the context of the Canadian workforce, as it directly and indirectly supports over 100,000 working individuals (CPC, 2023). Certainly, this information demonstrates the importance of the swine industry not only in the context of the Canadian economy but also for individual Canadians through employment opportunities. As such, it is imperative that the swine sector remains a viable and thriving industry, and for this assurance, all aspects of the swine production system must remain intact and reliable. To maintain this strong, vibrant, and profitable swine industry in Canada, it is necessary to ensure that disease transmission is minimal to non-existent. Thus, the introduction of stringent biosecurity measures, to the best of the industry capabilities, should be as unfailing as possible - a difficult challenge in a complex and highly integrated livestock industry.

For a livestock operation to be sustainable and profitable, it requires maintaining the daily needs of the stock animal while employing core principles to enhance production and performance. These needs include but are not limited to, diligent husbandry practices, such as proper housing with environmental control, excellent nutrition, and safeguarding against the introduction of infectious agents into the operation, commonly known as biosecurity. Failure to maintain any of these strategies will not only lead to reduced performance, production, and profitability but also undermine the health and welfare of the animals. Indeed, successful livestock

operations must invest significant resources to ensure these aspects of production are well maintained. This review explores the interplay of biosecurity regimens and breach points at the various levels of the swine production pyramid, particularly examining the interrelationships of herds with live animal and semen transportation, as well as embryo transfer throughout the swine industry. In addition, using various examples from the literature, this review examines various breach points, how these failed breach points increase the potential transmission of disease impacting swine health, and importantly, demonstrates the benefit of preventing breaches in biosecurity in swine production systems.

2. Swine Operation

The classical three-tier swine production management system is composed of three strata: nucleus, multiplier, and commercial herds, as presented in Figure 1. In general, nucleus herds represent the smallest proportion of producers and consists of F0 genetically superior purebred lines of pigs (Abell et al., 2010; Lopes, 2016; Vinje et al., 2023). The nucleus herd also strives to optimize reproductive efficiency in the dam lines (Knox, 2014). Indeed, optimized reproductive efficiency within the nucleus herd is an important consideration in enhanced swine production and profitability, with reproductive efficiency being defined as the number of viable offspring per breeding animal within a given time period (Dziuk & Bellows, 1983; Koketsu et al., 2017; Melton, 1995). Nucleus breeding centres provide stock pigs for both multiplier and commercial herds (Lopes, 2016). Although all tiers of the swine production system are susceptible to the inadvertent contamination of pathogens from various sources; due to the inherently high value of pigs within the nucleus herds, these herds maintain the highest level of biosecurity or lowest risk of pathogen introduction and operate within a closed management system (Grøntvedt et al., 2011; Ramirez & Zaabel, 2012). The intermediary producers are multiplier herds which rear replacement stock by crossbreeding different F0 nucleus stock and subsequently supply commercial production with the F1 generation (Ali et al., 2019; Lopes, 2016). The multiplier herds do not operate as a closed herd system; hence, the simple movement of animals between the nucleus and multiplier herds increases the risks of breaches in biosecurity (Knox, 2014). Lastly, commercial herds rear pigs to supply pork products, this represents the largest segment of the swine production system and is separated into two primary groups: finisher and farrow-to-finish operations (McBride & Key, 2014; Silva et al., 2019). The finisher operations provide F1 pigs to be grown to slaughter weight, whereas farrow-to-finish operations crossbreed the F1 generation to yield F2 market hogs (Bichard, 1971; Knox, 2014). Notably, because of the complexity of commercial operations and, in particular, the movement and mixing of different animals, commercial herds have the highest potential for breaks in biosecurity and the introduction of different infectious agents into the swine production system (Alarcón et al., 2021). Indeed, commercial operations may have the highest increase in infectious disease prevalence compared to the other two management operations (Holtkamp et al., 2013). In summary, there is a general trend of increased risk of diseases due to reduced biosecurity down the production pyramid, as illustrated in Figure 1. However, each stratum may have some unique aspects for maintaining effective biosecurity measures. Hence, several basic principles regarding biosecurity can be applied to all tiers of swine production.

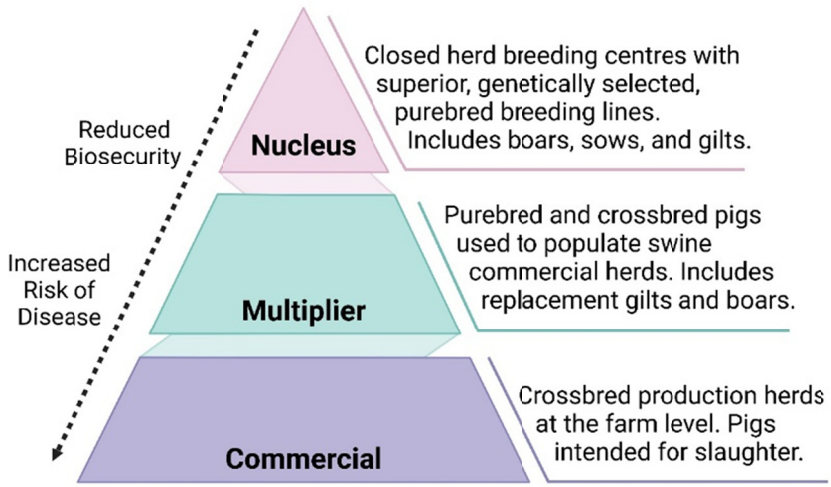

Figure 1. Swine production pyramid and their interrelationships in the industry

Note. Created in BioRender.com (BioRender.com/w48z009).

3. Biosecurity

Diligent biosecurity is a critical component for maintaining a healthy swine operation and improving producer profits (Nitovski et al., 2012; Postma et al., 2016; Stanković et al., 2010). Indeed, simple improvements to biosecurity in commercial operations, such as better cleaning and disinfection protocols, using specific pathogen-free pig stock, and donning clean clothing, have previously been shown to improve average daily weight gain and reduce pre- and post-weaning piglet mortality, collectively increasing profitability and improving animal health and welfare (de Roest et al., 2023). In general, effective biosecurity can be considered as the implementation of procedures to reduce the incidence, prevalence, and transmission of infectious agents within an operation (Youssef et al., 2021). To ensure effective biosecurity, identifying and managing various aspects of the farm that could involve a biosecurity breach point is essential (Nitovski et al., 2012; Scollo et al., 2023). When implementing biosecurity measures in swine herds, the type and scale of production with farm-specific production goals should be considered (Klein et al., 2024; Pinto & Urcelay, 2003). That said, regardless of the type of herd, biosecurity can be broadly viewed either as: i) external and internal protective biosecurity procedures, ii) conceptual (primary level), iii) structural or bio-exclusion (secondary level), and iv) procedural (tertiary level) biosecurity (Alarcón et al., 2021; Renault et al., 2021; Torremorell, 2021). These concepts of biosecurity have notable similarities. External biosecurity involves the prevention of pathogen spread between multiple farms, whereas internal biosecurity refers to the mitigation of disease transmission within a singular farm operation (Postma et al., 2016). Conceptual biosecurity focuses on lowering disease transmission by increasing the distance between facilities, specifically the physical distance between swine barns. Structural biosecurity uses farm structures to prevent the introduction of pathogens, utilizing perimeter fencing, water and air filtration systems, showers, and changing units. Procedural biosecurity employs operational protocols to stop the movement of pathogens within the facility, such as the placement of foot baths at room entrances. Importantly, regardless of the categorization of biosecurity, these programs should be integrated as part of a comprehensive plan for optimal disease protection of animals within different swine operations (Huber et al., 2022).

The speed, duration, and extent of disease transmission can be influenced by various factors, including the transport of live animals, movement of personnel and their clothing between rooms and facilities, transportation equipment, geographic location of swine operations relative to other swine facilities, disinfecting protocols, regulatory frameworks pertaining to the storage of dead animals, and compliance to biosecurity protocols and procedures (Alarcón et al., 2021; de Roest et al., 2023). In addition, the severity of the disease (virulence of the pathogen and adverse health effects on pigs), its mode transmission, and potential detrimental economic outcomes determine the type and rigour of biosecurity measures required for mitigation (Wrathall et al., 2004). As such, the development of effective biosecurity protocols that provide financial benefits in a livestock sector with potentially narrow profit margins is of great importance (de Roest et al., 2023).

4. Breach Points

4.1 Live Animal

The movement of live animals is the most common form of transportation of animal stock. Certainly, ground transportation of pigs is a fundamental component of swine production. This includes the introduction of new breeding stock to different facilities, such as moving pigs from nucleus centres to multiplier and commercial herds, the transposition of commercial pigs to markets, and the shipping of animals for slaughter (Foxcroft et al., 2010; McGlone et al., 2014). The transposition of live animals is not without inherent risks and is considered the primary avenue for disease transmission (Lambert & D'Allaire 2009; Massacci et al., 2020). Indeed, live animal movement can be more associated with disease transmission than the movement of semen or embryos (Kuster & Althouse, 2016; Neumann et al., 2021). When transporting live animals, there are different sources for potential breaks in biosecurity leading to a facility-wide infectious disease outbreak. The breach points can occur anywhere within the inter-facility movement of pigs, which include: i) transport vehicles, ii) wildlife and pests iii) people such as farm employees, visitors, veterinarians, and pig handlers iv) body fluids, including nasal secretions, blood, and v) feces (Fasina et al., 2024; Roman et al., 2006).

Transportation trucks and trailers are the major sources of inter-facility disease transmission and have been associated with the spread of transmissible swine diseases. For instance, it was shown that auction markets and harvest facilities were potential locations where hauling trailers may be contaminated by pigs infected with enteric pathogens such as porcine epidemic diarrhea virus (PEDV) and that over 14% of trucks were contaminated with PEDV when assessed for the virus at slaughter plants (Boniotti et al., 2018; Lowe et al., 2014). In addition, the movement of infected pigs within transportation trucks can disseminate disease to many

different locations. An investigation tracking the movement of trucks between two geographical regions of commercial farms showed that over a 1-year period, different transport vehicles were linked between 2157 and 437 different farms in two regions, underscoring the potential for a truck to widely spread infectious pathogens (Galvis & Machado, 2024).

Although trucks and trailers are important fomites in the transmission of infectious diseases between facilities, people involved with transportation may also be a source of pathogen dispersal. The truck driver or truck cab may inadvertently harbour the pathogen, acting as a reservoir for disease transmission during the loading and unloading of pigs (Ruston et al., 2021). Other personnel involved in pig farms can also act as potential sources for initiating disease outbreaks. In a study investigating inter-herd transmission during a classic swine fever (CSF) epidemic, there were over 2400 potential contacts of naive pigs following a farm visit to an infected herd, significantly increasing the possibility of disease transmission within a non-infected herd (Stegeman et al., 2002). Other individuals, such as veterinarians or farm technicians, could be a source of disease transmission. This is, however, an unlikely event, as, in particular, veterinarians are highly trained professionals and knowledgeable in biosecurity protocols for production units. That said and depending on farm density within a region, veterinarians can have a large practice radius, visiting many production units and could unknowingly contaminate farms (Olofsson et al., 2014).

Wildlife represents a potential route of disease exposure to domestic pigs. The increasing interaction between swine operations and wildlife, often associated with loss of habitat, creates ‘closer proximities’ between wildlife species and swine units (Podgórski et al., 2020). This can subsequently lead to disease spread by direct contact between animals (aerosols, manure, venereal transmission) and contamination of water and feed supplies. Many wildlife species can be primary sources for disease transmission to domestic pigs, however, wild boars represent the greatest potential risk to infect domestic pigs. A recent systematic review of pig infections in Europe showed that wild boars were associated with 80% of all possible infections. In contrast, rodents, wild deer, wild carnivore canids, and birds represented substantially lower rates of infection: 7%, 6%, 5%, and 4%, respectively (Makovska et al., 2023). Interestingly, insect vectors are considered pests and are also associated with disease transmission to domestic pigs, having transmission rates (5%) similar to wild carnivore canids (Makovska et al., 2023). Nevertheless, pests can be overlooked when considering disease transmission, but with the low yet prevalent risk for disease spread, pest control should be an important consideration for disease management (Mellor et al., 1987; Olesen et al., 2018).

The proximity and density of swine farms within a geographical area is also a noteworthy biosecurity consideration to prevent inter-facility disease transmission (Hu et al., 2023). Alonso et al. (2014) concluded that a farm with PEDV-positive pigs was capable of spreading the genetic material of the virus up to 10 miles downwind from the premise through aerosolization. Similarly, another study analyzed the spatiotemporal distribution of foot and mouth disease (FMD) transmission between facilities and delineated that the highest risk posed was to farms within a 2 km radius of the original outbreak herd and in the same direction of wind gusts (Hugh-Jones & Wright, 1970). Hence, intensive pig production systems in close proximity should remain mindful of the health status of surrounding farms to reduce the risk of disease transmission (Hernández-Jover et al., 2016; Kim et al., 2005).

Direct disease transmission between pigs can occur through contact with infected body fluids and feces. Highly contagious swine viruses such as African swine fever (ASF), FMD, and CSF are easily transmitted through oral secretions. An investigation that examined virus particles within oral secretions showed that pigs administered with viruses intramuscularly and intranasally had high numbers of virus particles within collected oral samples. Notably, the viral particles for ASF and FMD were collected prior to the onset of clinical signs of the disease (Grau et al., 2015). Virally infected blood can be a reservoir for disease transmission. Studies exploring the transmission of ASF between pigs showed that this virus was easily transmitted between pigs as a blood meal from biting insects or by the oral ingestion of insects carrying the virus. For example, stable flies that ingested blood with high ASF virus titers transmitted the disease to a healthy pig. These stable flies were able to transmit the disease for up to 24 hours post-infective feeding (Mellor et al., 1987). In another study, Olesen et al. (2018) showed that up to 50% of pigs developed ASF following the ingestion of stable flies carrying high inoculums of the virus. Interestingly, only 20 stable flies carrying the virus were required to induce disease, signifying the relatively small number of infected insects needed to transmit highly contagious pathogens.

Fecal matter is a substrate that can harbour pathogens for extended periods of time and is a particularly important consideration for robust infectious agents that can easily survive within the environment. A field study that examined infected farms with PEDV assessed the viability of the virus in open earthen manure storage units. The research showed that the virus survived up to 9 months in the storage units with the highest levels of viral load in

the lower layers of the manure collection unit (Tun et al., 2016). Another study demonstrated the transmissibility of viruses through fecal material, in which animals inoculated with PEDV were co-mingled with naive pigs to induce disease. It was shown that the virus was present in the fecal samples of all pigs for up to 14 days post-exposure and that every pig displayed clinical signs of disease, confirming that fecal contact is a proven route of disease transmission (Crawford et al., 2015). The information provided demonstrates how various sources can easily transmit infectious disease in live pigs and that sound biosecurity methods, with or without the use of other methods of transportation (*i.e.*, semen transport, or embryo collection), are needed to maintain healthy herds.

4.2 Semen

Artificial insemination (AI) is a globally applied reproductive technology in livestock production systems, with an adoption rate above 90% and rising in the swine industry (Waberski et al., 2019). This reproductive biotechnology is employed at all levels of the production pyramid: nucleus, multiplier, and commercial herds (Bortolozzo et al., 2024; Gerrits et al., 2005; Gonzalez-Peña et al., 2014). In general, the widespread use of AI has positively impacted swine biosecurity by reducing live animal transport and the transmission of diseases, while simultaneously improving reproductive efficiency through the utilization of a single ejaculate to produce numerous semen samples for insemination (Colenbrander et al., 1993; Rogožarski et al., 2014).

Semen can be a vector for disease transmission as it can be contaminated with an array of pathogenic microorganisms, the most prominent of which are Gram-negative bacteria (Costinar et al., 2021; Maroto Martín et al., 2010). The extent to which bacterial flora is present in raw semen samples varies substantially, with studies reporting positivity rates between 31-99% and an average amount of 82×10^3 CFU/mL of pathogens (Althouse & Lu, 2005; Ciornei et al., 2021; Paschoal et al., 2021). Contamination can occur by one of two methods, either directly (intrinsically) from the boar or indirectly (extrinsically) through non-animal sources (Althouse & Lu, 2005; Martins Pereira et al., 2013). Direct contamination and subsequent infection of females originates primarily from the testes, accessory glands, and preputial secretions of the boar or can be introduced from other biological materials such as fecal matter, respiratory secretions, skin, and hair (Costinar et al., 2021; Maroto Martín et al., 2010). Indirect contamination of semen samples can arise from improper handling techniques, personnel, collection or laboratory areas, water impurities, and other fomites (Althouse & Lu, 2005). There are variations in the acceptable limits of contamination in diluted semen samples, but the standard acceptable amount averages approximately 350 CFU/mL (Ciornei et al., 2021).

The risk for disease propagation in semen is highest when a boar presents with clinical signs of disease (Maes et al., 2016; Swenson et al., 1994). Moreover, the potential for semen contamination and the duration of the infectious period in boars and recipient females is importantly dependent on the type of pathogen (Guérin & Pozzi, 2005). As examples, it was reported that semen from porcine reproductive and respiratory syndrome (PRRS) positive boars remained infectious between days 2 and 10 post-inoculation of the virus (Prieto et al., 2003). Yaeger et al. (1993) demonstrated that gilts inseminated with semen from PRRS-positive boars resulted in seroconversion within 3-4 days post-AI. These findings have significant implications due to the fact that a single boar stud can serve between 200 to 10,000 breeding sows (Opriessnig et al., 2012). Likewise, the presence of high levels of infective live ASF virus and viral particles within the semen, testes, and accessory glands of experimentally infected boars was easily transmitted to gilts following AI (Friedrichs et al., 2022; Roszyk et al., 2022; Sehl-Ewert et al., 2023). In contrast to these studies, Meyer et al. (2017) investigated FMD, a highly virulent pathogen, specifically its effect on the ejaculates of bull cattle and concluded that the risk of semen infecting recipients was deemed low, estimated at 7.9×10^{-5} out of 100 collected semen samples.

Another potential breach point during the collection process is contamination of the ejaculate with preputial fluid. One study found that the prevalence of aerobic mesophilic bacterial growth averaged between 92-98% with preputial fluids, and there was a significant reduction to 62% contamination when preputial fluids were excluded from the sample (Goldberg et al., 2013). Furthermore, contamination was more prevalent when the collection process exceeded 7 minutes in duration, suggesting that increased exposure to preputial fluids increased the risk of pathogen transmission (Goldberg et al., 2013). Addressing such breach points is important to mitigate biological risk and reproductive inefficiency (Althouse, 2024; Dalmutt et al., 2020).

Indirect sources of semen contamination from non-animal origins are also possible (Maes et al., 2016). Schulze et al. (2015) highlighted that key breach points included heating cabinets, sinks, drains, laboratory surfaces, as well as personal items such as phones, and computer keyboards with evidence of bacterial counts above 10^3 CFU/cm^2. It was suggested that these may be unexpected sources that could cross-contaminate semen during processing. Biosecurity breaches can also occur from contaminated water filtration systems, which can contain

bacterial impurities (Kuster & Althouse, 2016). A semen distribution centre reported evidence of Gram-negative bacterial contamination from the water distillation system used to preserve semen (Payne et al., 2008). Collectively, as seen from the information provided, pathogen contamination of semen and semen products should not be underestimated on its adverse potential to impact animal health and swine performance. Indeed, it has been shown that up to 15% of the breeding stock can develop endometriosis following AI with contaminated semen, markedly affecting the long-term performance of recipient females (Payne et al., 2008). Therefore, identifying potential breach points prior to collecting and storing semen samples is crucial to ensuring the safe distribution of high-quality products (Maes et al., 2016).

4.3 Embryos

A good approach to disseminating swine genetics while safeguarding herd health and biosecurity is through embryo collection (Givens et al., 2007). Embryo dispersal, in contrast to the shipping of live animals and semen distribution, provides a superior means for reducing the transmission of disease (Men et al., 2012; Philpott, 1993). More specifically, Stringfellow et al. (1991) determined that high susceptibility for pathogen exposure occurs between day 0 to day 7 of embryo development, starting from ovulation until embryo uterine acclimation. Currently, the only approach to harvesting embryos from swine is either with live animal surgical intervention or immediately following slaughter (Martinez et al., 2017). Although the methodology to perform *in-vivo* embryo collections (*i.e.*, catheterization of the uterus with uterine flushing and embryo collection) requires further research and greater acceptance and implementation by the swine industry, such a discovery would allow for the collection, transport, and transfer of potentially sterile embryos; significantly reducing the risk of disease transmission and biosecurity breaches between herds (Hazeleger et al., 1994).

The transmission of disease by embryo is not without inherent risks, albeit with fewer risks compared to live animal and semen transportation (Thibier, 2011). Embryos may become contaminated with pathogens via: i) donor sow, ii) personnel involved with both media preparation and the embryo collection and transfer processes and iii) inter-facility transportation. In addition to these modes of transmission, there appears to be variabilities in the contamination of embryos, associated with the rate of infection and the agent. For example, Christianson (1992) attributed infectious disease-induced embryonic mortality to approximately 30% of reposted cases, while Mengeling et al. (1980) explored the relationship between porcine parvovirus (PPV) contamination and embryonic viability. Their study showed a lower incidence of embryo death; a total of 203 embryos were collected from PPV-positive sows, with 162 embryos being viable and non-infected, while 32 degenerating embryos were contaminated with PPV. Moreover, Pepin et al. (2024) screened 21 different pathogens in porcine oocyte maturation media and only detected positive results for porcine endogenous retrovirus type C in embryos. Additionally, embryos can serve as a reservoir of disease, infecting the recipient dam. Wrathall and Mengeling (1979) transferred 19-21 early-developing PPV-infected embryos into 4 seronegative gilts. After 8 days, all donors had seroconverted and developed moderate to high viral titers with clinical evidence of severe infection in the reproductive tract (Wrathall & Mengeling, 1979).

The potential for infected donor sows to transmit pathogens to embryos, however, is not consistent (Randall, 1999). Specifically, 145 four-cell to early morula staged embryos (94 unwashed, 51 washed) were transferred from PRRS-positive sows into seronegative recipients, and all the embryos were negative for the presence of PRRS virus (Randall, 1999). James et al. (1983) investigated disease transmission in embryos exposed to porcine pseudorabies virus (PRV). Embryos were recovered from 38 PRV-seropositive sows, with 805 embryos transferred to 34 PRV-seronegative recipients. Following farrowing, all 208 piglets and recipient sows remained seronegative, and there was also no detected virus within the embryo recovery medium (James et al., 1983). Although not fully determined, it's possible the discrepancies in embryo infectivity presented in the different studies may be due to the differences in the binding capability of pathogens to the outer surface of the zona pellucida (Macháty et al., 1998; Van Soom et al., 2010).

5. Mitigation Strategies for Disease Transmission

5.1 Live animal

Preventing the transmission of infectious diseases within swine operations is of critical importance. As an example, modelling estimates of an outbreak of ASF in Canada would cause devastation to the pork industry. Over a 2-year period, economic and animal projections included the humane destruction (welfare slaughter) of 14-21 million pigs and economic losses reaching approximately $11 billion (CAD) (Biden et al., 2024). As such, it behooves swine producers to develop strategies to both prevent and mitigate breaches in biosecurity.

Transportation trucks and trailers are proven sources of inter-facility pathogen transmission and are considered a primary critical checkpoint to reduce the spread of disease by lowering the pathogen load. One method of

reducing transmission includes limiting interactions between pig handlers and non-farm staff, such as the truck drivers involved in the loading and unloading of pigs. Ruston et al. (2021) illustrated that limiting the contact between different personnel with separation buffer zones reduced the potential spread of contaminants and pathogens during trailer loading of pigs. The adequate cleaning and disinfecting of transportation trucks is an effective method to reduce pathogen numbers, however, it can be challenging due to the lack of standard trailer cleaning protocols. For instance, a study that looked at transport vehicle sanitation with incremental improvements in the sanitation procedure: progressing from removing soiled material to removing soiled material with washing, disinfection and room temperature drying, demonstrated a near 100% reduction in PRRS trailer contamination (Dee et al., 2004). In contrast, trucks contaminated with PEDV showed that 46% remained contaminated following only washing and decontamination (Boniotti et al., 2018). The variance is likely due to both the different sanitation protocols and the resilience of PEDV within the environment; showing the importance of using good sanitation procedures and the ways in which the environmental hardiness of a pathogen can influence decontamination efficacy.

Controlling the pathogen load in transport trailers can also be reduced by heating trailers. This is a relatively new concept, but due to the rapid turnaround time and efficacy, it is considered a useful step in the decontamination process. In Canada, it's recommended that trailers are heated to 71 °C for 10 minutes as this was effective at reducing enteric pathogen loads (CFIA, 2021). Other research has shown, however, that trailer heating temperature and time could vary depending on pathogen hardiness and surface materials, therefore, heating decontamination protocols could be tailored towards controlling specific pathogens carried by the pigs (Mil-Homens et al., 2024; Van Kessel et al., 2020). Reducing personnel contamination is another effective method to reduce the transmission of diseases. Establishing protocols to enhance the biosecurity of animal movement between facility rooms or diminishing fomite transmission on clothing are effective strategies to reduce disease spread. Indeed, enhanced cleanliness and proper sanitation procedures reduced facility room-to-room fomites (hands, boots, coverall) transmission of PRRS in a research setting (Otake et al., 2002). Moreover, within a large commercial operation, Anderson et al. (2018) demonstrated that simply adding a bench to help staff remove their outside shoes tended (although not consistently) to reduce the transmission of contaminants on the 'clean side' following showering.

5.2 Semen

Semen ejaculates must be collected, processed, and stored using a thorough sequential procedure directed at effective sanitary control (Bussalleu & Torner, 2013). Implementation of stringent biosecurity procedures, such as washing the boars 2 days prior to collection, emptying the preputial diverticulum, and use of clean gloves, has previously demonstrated effective reductions in bacterial content. It has been shown that bacterial loads were significantly reduced from 18.8×10^3 CFU/mL to 490 CFU/mL when these procedures were implemented (Dias et al., 2000). Other protocols to reduce pathogen contamination have been applied for semen collection. These include: fog spraying with a decontaminant in the collection room 15 min prior to semen collection, using latex gloves while handling semen, as well as removing urine and other secretions within the prepuce. Notably, these procedures were effective at reducing bacterial and fungal contamination by 49.85% and 9.67%, respectively (Ciornei et al., 2021). Double gloving during semen collection further reduced the bacterial load in ejaculates, an easy procedure that can improve semen quality (Lellbach et al., 2008). Semen preserved in liquid form with semen extenders can reduce pathogen contamination (Hamonic et al., 2016; Knox, 2016). For instance, Vyt et al. (2004) demonstrated that bacterial counts in semen increased over time from 24 hours (4.89 log CFU/mL) to 72 hours (5.24 log CFU/mL) when stored without a semen extender. In contrast and measured at the same time points, there was a substantive reduction in the presence of bacteria sampled from 0.96 log CFU/mL to 0.44 log CFU/mL following the addition of an extender to the collected semen sample.

Environmental controls such as air filtration systems can also serve as a safeguard against aerosol transmission of microbial agents (Reicks, 2019). The presence of an air filtration system reduced outbreaks of PRRS infections in boar stud facilities from 53% to 11%, and notably, if disease outbreaks did occur, these were limited to 9-year intervals as compared to biennially prior to the addition of air filtration systems (Reicks, 2014). Lastly, another strategy to minimize the spread of disease between boars and dams through semen transmission can be achieved with sound vaccination programs (Jeong et al., 2017). A comparative analysis between unvaccinated and vaccinated boars for two strains of PRRS demonstrated that vaccinated boars did not transmit the virus within semen, whereas the unvaccinated sires shed the virus for up to 42 days following the virus challenge (Jeong et al., 2017). From the evidence above, the application of several mitigation strategies in boar stud facilities prior to, during, and following semen collection is vital to reduce intra- and inter-facility disease

transmission and to promote the safe distribution of uncontaminated semen (Colenbrander et al., 1993; Nitsche-Melkus et al., 2020).

5.3 Embryos

Similar to the mitigation strategies employed while transporting live animals and semen, procedures also exist to reduce the spread of disease during embryo collection (Gard & Stringfellow, 2014). The health of the donor and recipient dam should be evaluated prior to undergoing embryo techniques (Givens et al., 2007; Stringfellow & Givens, 2000). By implementing health measures, including disease screening and employing effective vaccination regimens to maintain healthy animals, the odds of collecting disease-free and viable embryos are improved (Gard & Stringfellow, 2014; Givens et al., 2007). Furthermore, embryos with an intact zona pellucida (days 4-6 post-fertilization) can serve as an innate protective barrier against pathogens in early-stage embryo development and are superior to post-hatched, pre-implantation embryos (Eaglesome et al., 1980; Givens & Marley, 2008).

If pathogens adhere to the embryo, washing protocols can be used to clean collected embryos, albeit the effectiveness of cleaning is variable and correlated to the stage of embryonic development and the integrity of the zona pellucida (Peltoniemi et al., 2019; Singh et al., 1986; Smith & Grimmer, 2000). Singh et al. (1986) reported that repeated washes of virally exposed porcine embryos caused a reduction in viral load, with only 2% to 4% of the embryos retaining viral particles following four sequential washes. Furthermore, it was reported that the growth of embryos exposed to swine vesicular disease virus was not impaired, as 86% of unexposed and 85% of exposed embryos were fully developed. This suggests that the virus was unable to readily penetrate the zona pellucida or replicate in the inner embryonic cells (Mateusen et al., 2004; Singh & Thomas, 1987). The innate fragility of newly developing embryos is another method that can stop the transmission of disease between males and recipient females. For instance, if early-developing embryos are exposed to a pathogen and succumb to infection, they can rapidly degenerate, preventing embryo implantation, and thereby halting the cycle of disease transmission between pigs (Stringfellow et al., 1991). Lastly, the personnel involved in the embryo collection procedure require proper training in aseptic technique and the handling and care of collected embryos. Antibiotics can also be added to the embryo media, further reducing the risk of bacterial contamination following the harvesting of embryos from donor sows (Thibier, 2011). In summary, embryos have intrinsic cellular properties such as the zona pellucida that can potentially reduce the likelihood of disease transmission during embryo transfer. Aligning these properties with other strategies, such as embryo washes and employing healthy stock animals, makes embryo transfer a sound choice for reducing disease transmission within swine operations (Gard & Stringfellow, 2014; Shisong & Wrathall, 1989; Stringfellow & Givens, 2000). Despite the biosecurity benefits of using embryos to disseminate genetics in swine, currently, the specialized skills, equipment and facilities required to effectively conduct embryo collection and transfer are prohibitive. Any commercial applications of embryo transfer in swine have been limited to the most valuable animals at the top of the production pyramid where the cost can be justified (Martinez et al., 2016).

6. Conclusion

Due to the significant role of the swine industry and pork production in the Canadian economy, it is imperative to identify and limit potential biosecurity hazards throughout the three herds involved in swine production. Although there can be variability (*i.e.*, difference between individual facility protocols and the proper implementation of biosecurity procedures), in general, the risk of infectious disease transmission is primarily associated with the transportation of live animals, with a lesser extent being linked to semen and embryo distribution. Live animal transport presents the highest risk factor due to the inter- and intra-facility disease outbreaks that can arise from transportation trucks and trailers, wildlife, pests, personnel, aerosols, and manure. In contrast, providing semen for AI reduces the risk of disease transmission, although problems can develop if proper sanitary control protocols are not followed, as ejaculates contain characteristically high microbial loads. Lastly, porcine embryo collection and transfer presents the industry with a novel method of disseminating genetic material while bearing lower risk to biosecurity. Transferring early-stage, unhatched embryos can further reduce the risk of pathogen transmission. In summary, regardless of the method used to distribute genetic material throughout the swine industry (*i.e.*, live animal, semen, or embryo transport), effective biosecurity practices are crucial for maintaining healthy swine herds and preventing virulent diseases from adversely affecting swine production and performance.

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