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Review

Pork as a Source of Diverse Viral Foodborne Infections: An Escalating Issue

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Abstract: This review synthesizes current knowledge on the risks posed by viral foodborne infections associated with pork, emphasizing their global prevalence and the complexity of managing such pathogens. It covers a range of significant viruses, including hepatitis A and E, norovirus, rotavirus, sapovirus, enterovirus, astrovirus, and enteric adenovirus. The role of pigs as reservoirs for diverse pathogens with zoonotic potential further complicates safety challenges, extending risks to individuals involved in pork production and processing. Various factors influencing viral contamination throughout the meat production chain are explored, from farm-level practices to processing and handling procedures. Emphasis is placed on the critical importance of implementing effective control measures at each stage, including enhanced biosecurity, rigorous hygiene practices, and appropriate thermal processing techniques. Additionally, the need for improved surveillance and detection methods to effectively identify and monitor viral presence in meat products is highlighted. In conclusion, the necessity of adopting a One Health approach that integrates efforts in animal health, food safety, and public health to mitigate the risks of viral foodborne infections associated with meat consumption is underscored. This holistic strategy is essential for safeguarding consumer health and ensuring the safety of the global food supply.

Keywords: pig; virus; pork; diversity

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1. Introduction

The necessity to uphold sustainable food production systems has become increasingly imperative, especially as global meat demand escalates in response to population growth and evolving dietary preferences. Among various animal-source foods, which collectively contribute to a third of the protein consumed worldwide, meat is a crucial nutritional component [1]. Since 1961, global meat production has seen a dramatic fourfold increase, primarily driven by significant consumer demand in Asia, with Europe and North America also contributing substantial volumes [2]. According to the latest reports, poultry is the leader in global meat production. Meanwhile, pork holds its place as the second most produced meat type, closely mirroring the trends in poultry with an anticipated stabilization of around 131 million tons in the near future [3].

Pork, integral to many traditional cuisines around the world, continues to be highly favored despite shifting dietary trends, with consumption rates in countries like Spain and Germany significantly exceeding global averages. For example, in 2020, Spain reported the highest per capita pork consumption at 52 kg, closely followed by Germany at 44 kg, and substantial figures from other major consumers like China and the United States. In Poland, pork consumption not only remains high but has shown an increase of over 13% in just three years, highlighting its enduring preference among consumers [2].

However, the widespread consumption of pork also introduces significant public health risks, primarily through foodborne infections. The global burden of these illnesses is considerable, with the World Health Organization (WHO) reporting millions of cases annually that result in significant morbidity and mortality. Despite the nutritional benefits of pork, its popularity necessitates rigorous and enhanced control measures throughout the production and supply chain to mitigate these health risks effectively [4].

Current practices in meat safety evaluation, particularly at slaughterhouses, are predominantly focused on bacterial pathogens and parasites, with viral agents often receiving inadequate attention. This oversight is concerning given the resilience and infectious potential of several foodborne viruses, such as hepatitis E and norovirus, which are known to persist in pork products that are raw or insufficiently cooked [5]. These viral pathogens can cause severe health outcomes and are capable of eluding standard processing treatments that typically neutralize bacterial contaminants [4].

This paper aims to explore the epidemiology of these viruses, assess their public health impact, and advocate for comprehensive, integrated food safety measures. These measures include enhanced surveillance, improved hygiene practices throughout the meat processing chain, and a more rigorous regulatory framework that addresses the unique challenges of controlling viral contaminants in pork. By addressing these issues systematically, this paper seeks to contribute to the broader goal of safeguarding public health while ensuring the sustainability of global pork production.

In our study, we conducted a meticulous screening of 127 papers to focus on the most significant viral diseases potentially linked to pork consumption. We performed a thorough literature review using multiple sources, including Scopus, the National Center for Biotechnology Information (NCBI), and Google Scholar. The keywords used included "viruses in food", "viruses in pork", "viruses + pork", "meat consumption", and "viruses in meat", among others. Papers were selected based on their relevance, publication dates, and peer-review status.

2. Pigs as Hosts of Multiple Viruses: The Complexity and Implications of Viral Diversity in Swine

Pigs are hosts to a diverse range of viral pathogens that pose significant threats to both animal health and public safety. Throughout their lives, swine can harbor critical viruses such as African swine fever virus (ASF), classical swine fever virus (CSFV), porcine reproductive and respiratory syndrome virus (PRRSV), porcine epidemic diarrhea virus (PEDV), and Aujeszky's disease virus (ADV). ASF and CSFV, for instance, are notorious for their high mortality rates, leading to devastating economic losses in pig farming industries. ASF, caused by a DNA virus, is characterized by hemorrhagic fever with mortality rates approaching 100%, while CSFV, an RNA virus, induces severe systemic disease [6]. PRRSV, another RNA virus, primarily affects respiratory and reproductive systems, causing significant losses due to reproductive failure and pneumonia [7]. PEDV, a coronavirus that contains RNA, results in severe diarrhea and dehydration, especially fatal in piglets [8]. ADV, also known as pseudorabies virus, is a DNA virus that affects the central nervous system, causing encephalitis and respiratory issues [9].

Transitioning from these high-impact diseases, swine are also susceptible to viruses of lower pathogenicity but persistent concern, such as parvoviruses and circoviruses, including porcine circovirus type 2 (PCV2) and type 3 (PCV3) [10]. PCV2 is particularly problematic due to its association with PCV2-associated diseases (PCVD/PCVAD) that can be subclinical or present with one or more clinical signs such as multisystemic disease with weight loss, high mortality, respiratory symptoms, dermatitis and nephritis, enteric signs including diarrhea, and reproductive disorders, leading to increased mortality and causing substantial economic losses in pig production [10]. Parvoviruses, with DNA genomes, cause reproductive failure and remain a constant threat despite vaccination efforts [11].

Building on the understanding of these diverse viral threats, the concept of an 'infectome', which refers to the collective array of an individual's infectious exposures associated with disease, helps in understanding the broad viral ecosystem within swine populations [12,13]. Advanced meta-transcriptomic studies aimed at quantifying the entire infectome of diseased pigs have uncovered a remarkable diversity of pathogens. These studies have identified 34 species of RNA viruses, nine species of DNA viruses, seven species of bacteria, and three species of fungi within afflicted swine populations. Notable among these are agents responsible for acute or severe diseases such as PRRSV, CSFV, and PEDV, alongside zoonotic pathogens like hepatitis E virus (HEV), rotavirus A, and Japanese encephalitis virus (JEV). HEV, for example, can be transmitted to humans through the consumption of undercooked pork, leading to hepatitis [14]. Rotavirus A is a leading cause of gastroenteritis in young pigs and can also infect humans. JEV, primarily affecting swine and horses, can cause severe neurological disease in humans [15].

Further expanding on the spectrum of viral agents, a significant portion of the detected pathogens are linked to milder or subclinical presentations, deemed opportunistic, such as sapoviruses, astroviruses, parvoviruses, herpesviruses, porcine respirovirus 1, and rotaviruses B, C, and H [13]. These pathogens, while not causing severe disease under normal circumstances, can still contribute to the overall burden of illness and complicate disease management strategies. For example, sapoviruses and astroviruses, primarily causing mild gastroenteritis, can exacerbate conditions in immunocompromised animals [16].

This extensive diversity of viral agents in pigs complicates disease control efforts and amplifies the risk of zoonotic spillover. Pigs, often acting as amplifying hosts for several viruses with zoonotic potential—including diverse strains of influenza viruses from avian, swine, and human hosts—play a pivotal role in the ecology of influenza viruses [17]. Their unique position as 'mixing vessels' facilitates the emergence of novel pandemic strains through interspecies transmission and genetic reassortment, posing a grave risk to global health [18]. The substantial variety of viruses that pigs host presents a complex challenge in veterinary and public health domains. As they navigate a spectrum of pathogens, pigs are not merely affected hosts but are crucial in bridging the gap between animal diseases and human infections [19]. This complex viral ecosystem underscores the need for vigilant surveillance, robust biosecurity measures, and innovative disease management strategies to mitigate associated risks. Understanding the full scope of the swine infectome—from deadly diseases like ASF and CSFV to less virulent but persistent viruses—is critical in devising effective control measures and preventing potential global health crises [20]. As ongoing research continues to unravel these viral interactions, the role of swine in disease ecology remains a focal point in safeguarding both animal and human health amidst an ever-evolving viral landscape.

3. Characteristics of the Foodborne Viruses in Pork

Foodborne viruses found in pork are typically shed in feces and transmitted via the fecal–oral route. These viruses can be categorized into three main groups: gastroenteritis-causing viruses, enterically transmitted hepatitis viruses, and viruses that replicate in the intestines with extraintestinal manifestations [4]. The brief characteristics of the foodborne viruses that can be identified in pigs and pork are presented in Table 1.

Table 1. Characteristics of the viruses detected in pork.

Virus	Size	Shape	Genetic Material	Host	Route of Transmission	Clinical Symptoms in Human	References
Adenovirus	70–100 nm	Non-enveloped icosahedral	Double-stranded DNA	Humans and animals	Respiratory droplets, fecal–oral, aerosols	Respiratory infections, gastroenteritis, conjunctivitis	[21]
Aichivirus/Kobuvirus	30–32 nm	Non-enveloped icosahedral viruses	Positive-sense ssRNA	Pigs	Fecal–oral	Gastroenteritis, diarrhea	[22,23]

Table 1. *Cont.*

Virus	Size	Shape	Genetic Material	Host	Route of Transmission	Clinical Symptoms in Human	References
Astrovirus	28–30 nm	Non-enveloped icosahedral	ssRNA	Over 80 host species, including humans, bats, companion animals (dogs and cats), and livestock (pigs, chickens, and cows), as well as wild animals such as wild boars and rats	Fecal–oral	Asymptomatic or systemic; diarrhea and gastrointestinal symptoms, gastroenteritis, encephalopathy in immunocompromised individuals	[24]
Coronaviruses	80–120 nm	Enveloped, spherical	Positive-sense ssRNA	Humans and animals	Aerosol, fomite, fecal–oral	Respiratory infections, fever, cough, pneumonia	[25]
Enterovirus	20–30 nm	Non-enveloped icosahedral	Positive-sense ssRNA	Humans	Fecal–oral	Poliomyelitis, meningitis, encephalitis, respiratory infections	[26]
Hepatitis A virus	27–32 nm	Non-enveloped icosahedral	Positive-sense ssRNA	Humans	Fecal–oral	Jaundice, liver inflammation	[27]
Hepatitis E virus	27–34 nm	Icosahedral	ssRNA	Humans, pigs, fruit bats, rats, and other animals	Fecal–oral, zoonotic, contaminated blood products, undercooked meat	Asymptomatic, acute viral hepatitis, fulminant hepatitis, chronic hepatitis, cirrhosis, extrahepatic manifestations	[28]
Highly pathogenic avian influenza virus	300 nm	Spherical	Negative ssRNA	Wild birds, poultry, wide range of wild mammals: foxes, lynxes, skunks, raccoons, bears, otters, polecats, badgers, ferrets, pumas, panthers, opossums, seals, porpoises, and sea lions, as well as dolphins	Aerosol, fecal–oral	Respiratory symptoms, neurologic symptom	[29,30]

Table 1. *Cont.*

Virus	Size	Shape	Genetic Material	Host	Route of Transmission	Clinical Symptoms in Human	References
Norovirus	27 to 40 nm	Non-enveloped icosahedral	Linear, single-stranded, polyadenylated RNA	Humans, pigs, cattle, sheep, dogs, cats, lions, rodents, bats, sea lions, harbour porpoises	Fecal–oral, air-borne, water-borne	Gastroenteritis: vomiting and diarrhea	[31,32]
Nipah virus	40–600 nm	Enveloped, spherical	ssRNA	Fruit bats (Pteropus conspicullatus), humans, pigs	Direct contact with infected animals, contaminated food	Fever, body aches, headaches, sore throat and vomiting, which can soon become complicated with neurological manifestations suggestive of acute encephalitis (dizziness, altered sensorium, myoclonic jerks, etc.)	[33,34]
Parvovirus	18–26 nm	Non-enveloped icosahedral	ssDNA	Humans and animals	Respiratory, fecal–oral	Rash, anemia	[35]
Rotavirus	60–80 nm	Non-enveloped icosahedral	Double-stranded RNA	Humans	Fecal–oral	Diarrhea, vomiting, dehydration	[36]
Sapovirus	27–40 nm	Non-enveloped icosahedral	Positive-sense ssRNA	Humans	Fecal–oral	Gastroenteritis, diarrhea, vomiting	[37]

3.1. Gastroenteritis-Causing Viruses

Gastroenteritis-causing viruses that can affect pigs and potentially humans include noroviruses, rotaviruses, astroviruses, adenoviruses, and sapoviruses. These viruses primarily cause acute gastroenteritis characterized by vomiting and diarrhea [4].

Noroviruses are highly contagious and the most common cause of viral gastroenteritis worldwide [38]. They have been detected in various food animals, including pigs, presenting a potential zoonotic risk. Noroviruses can cause outbreaks in semi-closed settings and are transmitted through contaminated food, water, and surfaces [39]. In pigs, norovirus infections are often asymptomatic but can contribute to enteric disease, especially in young animals [40]. Human norovirus-like sequences have been detected in pigs, raising concerns about potential cross-species transmission [41]. Symptoms in humans typically include nausea, vomiting, stomach pain, watery diarrhea, low-grade fever, and muscle pain, beginning 12 to 48 h after exposure and lasting 1 to 3 days [42].

Rotaviruses primarily affect young pigs and children, causing severe diarrhea, vomiting, fever, and abdominal pain [43]. In swine, rotavirus infections can lead to significant economic losses due to reduced growth rates and increased mortality in piglets [44]. The virus spreads through the fecal–oral route via contaminated hands, surfaces, or food [43]. In humans, symptoms typically start within 2 days of exposure and last 3 to 8 days [45].

Rotaviruses are highly stable in the environment, facilitating their spread in both swine herds and human communities [44].

Astroviruses cause mild gastroenteritis in pigs, particularly affecting young animals. In swine, astrovirus infections can be asymptomatic or cause mild diarrhea, but co-infections with other enteric pathogens may lead to more severe disease [46]. Porcine astroviruses have been identified in healthy pigs and those with diarrhea, suggesting their role in swine health is complex [47]. In humans, symptoms include diarrhea, nausea, vomiting, fever, malaise, and abdominal pain, usually self-limiting and lasting 3 to 4 days [48]. The prevalence of astroviruses in pigs suggests potential zoonotic transmission, though more research is needed to fully understand this aspect [49].

Adenoviruses can cause gastroenteritis, respiratory illnesses, and other infections in pigs [50]. Porcine adenoviruses have been associated with various clinical conditions in swine, including pneumonia, encephalitis, and diarrhea [51]. While less commonly linked to foodborne transmission in humans, they can spread through contaminated food, water, and surfaces [52]. Adenoviruses are hardy, surviving on surfaces for extended periods, making them difficult to control in both swine production environments and human settings [53].

Sapoviruses cause gastroenteritis in pigs and humans, particularly affecting young animals and children [54]. In swine, sapoviruses have been detected in both healthy and diarrheic pigs, with some strains showing potential for zoonotic transmission [55]. Symptoms in humans include diarrhea, vomiting, abdominal cramps, and fever. Like noroviruses, they are highly contagious and can persist in the environment, leading to widespread transmission in affected areas [56].

3.2. Enterically Transmitted Hepatitis Viruses

This group includes hepatitis A virus (HAV) and hepatitis E virus (HEV). Both viruses initially infect the intestines but subsequently migrate to the liver, causing hepatitis.

HAV is a non-enveloped, single-stranded RNA virus belonging to the Picornaviridae family. It is primarily transmitted through the fecal–oral route by ingestion of contaminated food or water. Key characteristics of HAV include its transmission primarily through contaminated food and water but also through close personal contact with infected individuals [57]. The symptoms of HAV include liver inflammation characterized by jaundice, fatigue, abdominal pain, nausea, fever, dark urine, and pale stools, typically appearing 15–50 days after exposure [58]. While HAV infections are usually self-limiting in healthy individuals, they can be severe in older adults and those with preexisting liver conditions. HAV is highly contagious, with infected individuals being most infectious 1–2 weeks before symptom onset [58]. Food safety concerns often arise from improper food handling and poor sanitation practices, as food handlers can transmit the virus if they work while infectious. Vaccination is the most effective prevention method, along with proper hygiene practices and safe food handling [59]. Although HAV is not typically associated with pork products, it can contaminate any food through infected food handlers or contaminated water used in food processing [59].

HEV is a non-enveloped, single-stranded RNA virus of the Hepeviridae family. It is increasingly recognized as an important foodborne pathogen, particularly in relation to pork products. HEV is primarily transmitted through contaminated water in developing countries, but in developed countries, it is often associated with the consumption of undercooked pork and wild game meat [60]. HEV, particularly genotypes 3 and 4, can infect both humans and animals, with pigs serving as a major reservoir [61]. The symptoms of HEV are similar to those of HAV, including jaundice, fatigue, abdominal pain, nausea, and fever, typically appearing 2–10 weeks after exposure. HEV can cause severe liver disease, especially in pregnant women and immunocompromised individuals, and chronic infection can occur in immunosuppressed patients. Food safety concerns arise from the detection of HEV in pork liver and other pork products, particularly when undercooked [62]. HEV can survive in the environment and resist food production processes typically used to control bacterial pathogens. Preventing HEV involves proper cooking of pork products (especially liver) to an internal temperature of 71 °C, good hygiene practices, and a safe water supply [63,64].

3.3. Viruses Replicating in Intestines with Extraintestinal Manifestations

Viruses in this group, such as enteroviruses, replicate in the human intestines but cause illness after migrating to other organs, like the central nervous system. Additionally, some viruses not typically considered foodborne, such as severe acute respiratory syndrome (SARS)-coronaviruses and highly pathogenic avian influenza virus (HPAIV), may occasionally be transmitted through food [65].

Enteroviruses are a diverse group of viruses that can cause a range of illnesses, including hand, foot, and mouth disease, myocarditis, and aseptic meningitis. These viruses, which belong to the Picornaviridae family, are small, non-enveloped, and possess a single-stranded RNA genome [66]. Enteroviruses are primarily transmitted through fecal–oral routes but can also spread via contaminated food and water [67]. Symptoms of enterovirus infections include fever, sore throat, rash, and gastrointestinal distress [68]. Severe complications can occur if the virus spreads to other organs, such as the heart or brain, leading to conditions like viral meningitis or encephalitis [69]. These viruses are highly adaptable and can persist in the environment, contributing to their widespread transmission, especially during the summer and fall seasons when infections are most common [70].

SARS-coronaviruses, although primarily respiratory pathogens, have been detected in foodborne transmission scenarios, particularly through contaminated meat products [71]. SARS-CoV-2, the virus responsible for COVID-19, is mainly transmitted via respiratory droplets, but there is some evidence suggesting it can infect intestinal cells [72]. However, the risk of transmission through food is considered very low [72]. The virus can survive on surfaces for extended periods, which underscores the importance of stringent hygiene practices in food handling and preparation [73]. Symptoms of SARS-CoV-2 infection include fever, cough, and shortness of breath, and in severe cases, it can lead to acute respiratory distress syndrome (ARDS) [74]. While foodborne transmission of SARS-CoV-2 is theoretically possible, it remains primarily a respiratory virus, and no significant evidence supports food—and pork in particular—as a major transmission route [75,76].

Highly pathogenic avian influenza virus (HPAIV) is rarely transmitted through food but poses a zoonotic risk through handling and consumption of contaminated poultry products [77]. HPAIV can cause severe respiratory illness in humans, with symptoms ranging from mild respiratory issues to severe pneumonia and death [78]. The virus spreads through direct contact with infected birds or contaminated surfaces [79]. Proper cooking of poultry to an internal temperature of at least 74 °C (165 °F) and strict biosecurity measures in poultry farms are crucial in preventing HPAIV transmission [80]. Human infections with HPAIV are rare but can occur, particularly among individuals who have close contact with infected birds or work in poultry processing [81].

It is known that not only poultry and wild birds, but also pigs, horses, dogs, and humans serve as long-term reservoir hosts for influenza A virus (IAV) [82]. Although there is no evidence of shedding or transmission of HPAI strains in inoculated pigs, the ability of avian isolates to replicate in the lungs raises concerns about potential reassortment with endemic swine viruses [83]. Therefore, we cannot dismiss the possibility of swine being involved in HPAI in the future. Additionally, since reassortment has occurred during the last four influenza pandemics, the chances of reassortment in swine could increase the risk of H5N1 adapting to humans, particularly due to the presence of 2009 pandemic H1N1 seasonal virus genes in pigs [83]. Although the occurrence of low pathogenic avian influenza (LPAI) in commercial swine herds in North America is infrequent, it does happen periodically, often with unidentified sources [83]. Research indicates that enhanced viral fitness, marked by the transmission of LPAI strains after reassortment with swine-adapted IAV in pigs, has been observed in both commercial herds and experimental conditions [83]. Furthermore, recent cases of HPAI H5N1 virus infection in cats in Poland, linked to meat consumption, emphasize the need to include *Mammalia* in the list of species that pose a significant risk for the spread of HPAI in Europe. This would equip health authorities with essential tools and guidelines for managing such cases, underscoring the potential threat [30].

4. Foodborne and Zoonotic Viruses: Occurrence and Distribution in Pork

4.1. Norovirus (NoV)

Research has identified human-like NoV strains in swine populations across multiple continents, prompting investigations into the role of pigs as potential reservoirs for these human viruses [42]. The prevalence of NoV in pig feces is generally low, typically not exceeding 16.6%, but it exhibits regional and seasonal variations [84]. Genetic analyses have uncovered a variety of NoV strains in pigs, notably including GII.18 and GII.4-like sequences. The latter is of particular concern as it is commonly associated with outbreaks in humans. Studies have detected GIII (bovine), GII.18 (swine), and GII.4 (human) norovirus sequences in animal fecal samples, demonstrating for the first time that GII.4-like strains can be present in livestock [85].

The presence of human NoV RNA in adult pigs and the detection of antibodies against human strains in swine underscore the real possibility of interspecies transmission. Antibodies recognizing human norovirus have been detected in healthy household pigs in Nicaragua and pigs in the US, with prevalences ranging from 52 to 70% [86]. Experimental infections have demonstrated that gnotobiotic pigs are susceptible to infection with human GII.4 strains, suggesting that pigs could serve as viable hosts for these viruses [87]. Moreover, the detection of GII.4-like noroviral RNA in retail meat samples points to the potential for indirect zoonotic transmission through the food chain [42]. This finding highlights a possible route for indirect zoonotic transmission of noroviruses through meat, dairy, or farm samples from infected pigs and cows.

Although current evidence does not conclusively prove that NoVs are zoonotic, the genetic similarities between porcine and human strains, along with the detection of human-like strains in pigs, emphasize the necessity for ongoing surveillance and research. The possibility of emerging porcine/human GII recombinants introduces additional complexity to managing this public health issue [88]. Water, food sources, and filter-feeding shellfish can harbor multiple human and animal genotypes and genogroups simultaneously, posing a possible source of co-infection in humans and animals [89]. These findings highlight the critical need for vigilant monitoring of NoV within swine populations and the implementation of stringent food safety practices throughout the pork production process to reduce the risk of public health impacts. To increase the chances of detecting transspecies transmission events, more targeted surveillance is needed, including samples from animals and humans in close contact, ideally during outbreak situations, and using unbiased detection methods.

4.2. Nipah Virus (NiV)

This virus exhibits significant genetic diversity, with two predominant lineages: NiV Malaysia (NiV-MY) and NiV Bangladesh (NiV-BD). These strains differ not only in their nucleotide sequences but also in their pathogenic profiles [90]; NiV-BD is noted for being more virulent and having higher rates of oral shedding than its Malaysian counterpart [91]. Confirmed cases of Nipah virus infections have been reported in several Asian countries, including Malaysia, Singapore, Bangladesh, India, and the Philippines [92]. The virus primarily resides in fruit bats of the *Pteropus* genus, which are asymptomatic carriers [93]. Transmission to pigs occurs when they consume fruits or water contaminated by these bats. Once infected, pigs can serve as amplifying hosts for the virus, facilitating further spread. The virus's ability to replicate in pigs poses a significant zoonotic threat [94]. Human infections typically arise through direct contact with the bodily fluids of infected pigs, such as saliva, urine, and other excretions, or by handling and consuming contaminated pork products.

In humans, NiV can lead to severe health outcomes, including respiratory distress and encephalitis, which often result in high fatality rates [93]. The majority of human cases linked to pig transmission have occurred in occupational settings, such as pig farms and abattoirs, where workers are in close contact with infected animals [95]. This mode of transmission emphasizes the critical need for stringent biosecurity measures and robust surveillance systems in these environments to detect and contain the virus promptly. Moreover, the occurrence of NiV in pork products further highlights the risks associated with inadequate cooking and handling practices. It is essential for pork producers and consumers to adhere to strict food safety protocols, including thorough cooking and proper hygiene practices, to prevent the potential spread of NiV through the food chain.

Given the serious implications of Nipah virus infections and the virus's noted persistence and adaptability, ongoing research and international cooperation are crucial to better understand its epidemiology, develop effective treatments, and implement preventive strategies to protect both animal and human health. Although no recent large-scale outbreaks in pigs have been reported, the potential for NiV to re-emerge in pork production remains a concern, especially in regions where fruit bats and pig farming coexist.

4.3. Hepatitis E Virus (HEV)

HEV genotypes 3 and 4 (HEV-3 and HEV-4) are zoonotic foodborne viruses that are endemic in pig populations worldwide and also prevalent in wild boar [96]. Despite the lack of routine monitoring for HEV, it remains a significant threat to consumers of pork and pork products. The seroprevalence of HEV in swine varies significantly across different countries, ranging from nearly 10% in Thailand to over 84% in India, with rates below 50% in countries such as Poland, Lithuania, France, Ireland, Serbia, Spain, Mexico, the USA, Uruguay, and Cameroon [97,98]. HEV RNA has been detected in various commercial pork products, indicating a significant risk for foodborne transmission. High prevalence rates have been found in specific pork products, including pork liver pâtés, dry-cured sausages containing pig liver, raw or undercooked pig liver, and game meat from wild boar [99]. The virus can survive in contaminated food and is resilient in the environment, posing a persistent risk.

Human HEV infections are typically linked to exposure to animal feces and the consumption of improperly cooked pork [61]. Although most HEV infections in humans are subclinical, they can become severe, particularly in individuals with preexisting liver conditions, pregnant women, and immunocompromised patients [100].

The transmission dynamics of HEV emphasize the need for thorough cooking of pork products to mitigate the risk of infection. Public health initiatives should focus on educating consumers about the risks associated with undercooked pork and the importance of proper food handling and preparation techniques. Additionally, the pork industry should implement and adhere to strict biosecurity measures to prevent HEV contamination along the production chain. This includes improved hygiene practices on farms and at slaughterhouses, regular testing of pigs and pork products for HEV, implementing age-segregated rearing systems to reduce transmission among pigs, and proper management of pig manure to prevent environmental contamination. Given the widespread distribution of HEV in pig populations and its potential impact on human health, enhanced surveillance and research efforts are crucial. Understanding the factors contributing to the variation in HEV prevalence and developing effective control strategies will be essential in reducing the burden of HEV-related diseases.

Future research should focus on developing standardized and sensitive methods for HEV detection in food products, investigating the effectiveness of potential control measures such as vaccination of pigs, and assessing the risk of HEV transmission through non-pork food products contaminated by pig feces. Addressing this zoonotic threat will require a coordinated effort from public health authorities, the pork industry, and consumers to implement effective prevention and control measures.

4.4. Aichivirus

Aichivirus, specifically belonging to the genus *Kobuvirus* in the family Picornaviridae, is a notable pathogen detected in pork and porcine products. The genus includes three species: Aichivirus A, Aichivirus B, and Aichivirus C. Porcine kobuvirus (Aichivirus C) is endemic to pig farms worldwide, with significant prevalence reported in several countries. Studies have revealed that Aichivirus C is commonly found in pig populations, with infection rates ranging from 24% to 84% in Italy and 27.2% in Spain [23,101]. In Canada, prevalence rates of enteric viruses, including kobuvirus, can reach up to 100%, depending on the age group of the pigs tested [102]. These findings indicate a widespread presence of kobuvirus among swine, which is often accompanied by other enteric viruses such as astroviruses, PEDV, porcine adenoviruses, and rotaviruses [101,102]. The virus is primarily associated with diarrhea and asymptomatic infections in pigs [103]. Genetic studies have shown significant diversity within porcine kobuvirus strains, suggesting that mutations and recombination events may play a crucial role in its evolution and spread [103]. The detection of kobuvirus in pig serum implies that the virus can escape the gastrointestinal tract and enter the circulatory system, potentially increasing the risk of meat contamination [104].

Although the presence of kobuvirus in pork products has not been extensively studied, the high prevalence of the virus in pig farms suggests a substantial probability of contamination, posing a risk to consumers [105]. The consistent detection of kobuvirus across various geographical regions highlights the importance of monitoring and controlling this virus within the pork industry. Implementing stringent biosecurity measures and proper food safety protocols throughout the pork production chain is essential to mitigate the potential public health risks associated with Aichivirus. These measures include improved hygiene practices on farms, regular testing of pigs for kobuvirus, and ensuring that pork products are thoroughly cooked to eliminate any potential viral contamination. Given the significant prevalence and potential impact of Aichivirus C on both animal and human health, ongoing research and surveillance are crucial. Understanding the factors contributing to the spread and evolution of porcine kobuvirus will be vital in developing effective control strategies. Enhanced biosecurity measures, coupled with public education on proper food handling and preparation techniques, will play a critical role in reducing the risk of Aichivirus transmission through pork products.

5. Contamination, Persistence, and Occupational Risks

5.1. Viral Contamination in Pork Production

Viral contamination can occur during primary production, especially for minimally processed foods, or through infected food handlers for ready-to-eat products [4]. In the context of pork, meat can be contaminated by excreta during processing or as a result of infection in living animals. Foodborne viruses are known for their resilience and persistence in the environment, often resisting mild food processing techniques that would inactivate bacterial pathogens.

The contamination of pork products by viruses can happen at various stages of the food production chain. During primary production, viruses can be introduced through contaminated water or soil. For pork, contamination can occur through contact with feces during slaughter and processing. Infected pigs can shed viruses in their excreta, which can contaminate their meat [106]. Additionally, food handlers who are infected with viruses can contaminate ready-to-eat foods through poor hygiene practices, such as inadequate handwashing [107].

5.2. Persistence of Foodborne Viruses

Foodborne viruses are particularly challenging to control due to their ability to persist in the environment and resist common food processing methods. Unlike bacterial pathogens, many viruses can withstand mild heat treatments, acidic conditions, and desiccation. For example, noroviruses and HAV can remain infectious on surfaces and in food products for extended periods [52]. The resilience of these viruses is further enhanced by the presence of certain food constituents. Ingredients like salt, sucrose, and fat can provide a protective effect, allowing viruses to survive heat treatments that would typically inactivate bacteria [108,109].

One of the significant challenges in managing foodborne viruses is the occurrence of asymptomatic infections. Individuals infected with viruses such as norovirus, HAV, and HEV may not exhibit symptoms but can still shed the virus in their feces [31,110]. This asymptomatic shedding can lead to the contamination of food and food production environments without detection. For instance, asymptomatic carriers of HAV can shed large quantities of the virus in their feces, contributing to the spread of the virus in food production and preparation settings. Similarly, asymptomatic shedding of HEV by infected pigs can contaminate pork products, posing a risk to consumers [111].

5.3. Hygiene Practices and Public Health Measures

The asymptomatic nature of some viral infections complicates efforts to control their spread in food production environments. Infected individuals may continue to work in food handling and preparation roles, unknowingly contaminating food products. This underscores the importance of stringent hygiene practices, regular health checks, and proper training for food handlers. Public health measures should include comprehensive hygiene protocols, such as thorough handwashing, regular disinfection of surfaces, and the use of personal protective equipment [97]. Moreover, the persistence of these viruses in the environment and their resistance to inactivation pose additional challenges. For example, noroviruses can survive on food contact surfaces made of various materials such as ceramic, glass, plastic, rubber, stainless steel, and wood for up to 28 days at room temperature [112]. This long-term persistence necessitates rigorous cleaning and sanitation protocols in food processing and handling facilities to prevent contamination.

According to the WHO, the impact of foodborne illness on society is devastating: every year, approximately 600 million individuals become ill, and 420,000 lose their lives due to unsafe food, leading to a loss of 33 million healthy life years (DALYs). Children under five are especially vulnerable, with 125,000 fatalities attributed to foodborne diseases annually. Most of these illnesses and deaths could be prevented [113]. The statistics related to foodborne viral diseases are still unknown.

The White Paper on Food Safety, published by the European Commission in 2000, marked a turning point in the European Union's approach to ensuring food safety. Its overarching goal was to establish a comprehensive and integrated system to safeguard public health, placing consumer protection at the center of EU policy. This document outlined essential principles and regulatory reforms aimed at minimizing risks related to foodborne illnesses, including those caused by zoonotic viruses [114].

One of the key tenets of the White Paper is the precautionary principle, which plays a critical role in mitigating potential risks posed by zoonotic viruses in pork and other food products, even in the absence of scientific certainty. This principle emphasizes that protective measures should be taken to safeguard consumer health, particularly concerning zoonotic viruses such as the hepatitis E virus (HEV), which can be transmitted through pork and pork products [115]. The precautionary principle ensures that public health authorities in the EU can take preventative actions—such as recommending cooking guidelines or restricting certain food practices—to reduce the risk of virus transmission, even if definitive scientific evidence about the scope of the threat is still emerging [114].

The White Paper introduced the concept of farm-to-table monitoring, ensuring that food safety is maintained throughout the entire production chain—from animal farming to food processing, distribution, and consumption. This integrated approach is essential for controlling zoonotic viruses and includes regular health checks on pigs, stringent processing standards, and hygienic measures throughout the supply chain [114].

The establishment of the European Food Safety Authority (EFSA) was another critical outcome of the White Paper. EFSA plays a central role in conducting scientific risk assessments related to food safety, including evaluating the risks posed by zoonotic viruses. Operating independently, EFSA provides scientific advice and data to support decision-making by EU policymakers.

EFSA has been actively involved in assessing the risks associated with zoonotic viruses in pork, particularly those posing a significant threat to public health, such as HEV. Their assessments focus on understanding the epidemiology of these viruses and their transmission routes and providing scientific advice on preventive measures to reduce the risk of foodborne illness. EFSA emphasizes the need for better monitoring in pig farms, slaughterhouses, and food processing plants, recommending strict hygiene practices and proper cooking of pork products [97,115].

Moreover, EFSA strongly advocates for increased surveillance and monitoring of zoonotic viruses in both the pig population and food products. They recommend routine testing of pigs, particularly in areas with a high incidence of HEV, to identify carriers and prevent the virus from entering the food chain. Additional screening measures in slaughterhouses and meat processing facilities for high-risk products have also been suggested [116].

EFSA highlights the importance of consumer education regarding the risks of consuming raw or undercooked pork products. They recommend informing consumers about the proper cooking temperatures needed to inactivate viruses. To prevent the spread of zoonotic viruses among pigs and reduce the risk of transmission to humans, stricter biosecurity measures on pig farms are recommended. These measures include improved hygiene practices, better management of pig herds, and controlling risk factors like pig transport and mixing of herds, which could increase viral transmission [117].

Strict hygiene controls during the slaughtering and processing stages are critical to preventing contamination of pork products with zoonotic viruses. Implementing Hazard Analysis and Critical Control Points (HACCP) principles, which focus on identifying and controlling potential hazards in food production, is recommended [118].

The use of modern food safety technologies, such as pathogen detection systems and traceability mechanisms, is encouraged to quickly identify and remove contaminated products from the food chain. EFSA has also pointed out several data gaps in understanding the full extent of zoonotic virus transmission through pork, including the prevalence of HEV in different pig populations across Europe and the effectiveness of various cooking methods in inactivating these viruses. To address these gaps, EFSA calls for more scientific research and collaboration between national food safety authorities, researchers, and the food industry [115].

Another important question relates to organic or sustainable pig farming, which emphasizes environmental sustainability, animal welfare, and the reduction of chemical inputs [119]. This approach seeks to minimize the environmental footprint of pig farming while producing healthier and more ethically raised animals. Eco-pig production prioritizes the natural behaviors and welfare of pigs, providing them with more space to roam, access to the outdoors, and opportunities for natural activities like rooting and foraging. The use of antibiotics is limited or avoided, focusing on preventive health measures through proper nutrition, hygiene, and biosecurity. Organic feed is used to reduce environmental impact, typically consisting of non-GMO crops grown without synthetic fertilizers or pesticides. The production also aims for low food miles and integrates pigs into broader agricultural systems to contribute to land regeneration and biodiversity [120].

There is a perception that organic or eco-friendly pork is healthier due to the absence of synthetic chemicals and antibiotics [119]. The meat may also have better nutritional quality, with higher levels of beneficial fats and vitamins. Pigs raised in more natural, less crowded environments experience lower stress, which can decrease the likelihood of disease outbreaks, including zoonotic viruses. Farms practicing eco-pig production often implement strict biosecurity protocols to prevent the spread of zoonotic diseases between wildlife, livestock, and humans. With fewer antibiotic treatments allowed, eco-pig farms must rely heavily on preventive measures and natural treatments, which can be challenging during disease outbreaks.

Overall, eco-pig production aligns well with sustainability goals and public health protection while supporting ethical farming practices. However, careful management is required to address both economic and health-related challenges effectively.

5.4. Zoonotic Transmission and Occupational Risks

The risk of zoonotic transmission presents significant challenges for both consumers and workers in the industry. Regions with culinary traditions that favor raw or undercooked pork products, such as metka sausage or cold-smoked meats, face an elevated risk of viral transmission [121,122]. These dishes, while culturally significant, can serve as potential vectors for foodborne viruses like hepatitis E virus (HEV), which is particularly associated with pork products [123]. The consumption of undercooked pork liver, for instance, has been linked to numerous cases of HEV infection in various countries. Occupational risks in the pork industry are equally concerning. Abattoir workers, veterinarians, and butchers are at the forefront of potential exposure to zoonotic viruses. These professionals routinely come into contact with live pigs, their blood, body fluids, and excretions, increasing their risk of infection through various routes. Skin lesions, mucous membranes, and inhalation of aerosols during the slaughter and processing of pigs can all serve as entry points for viral pathogens [124].

While viruses like HIV, SARS-coronaviruses, and Ebola are not typically associated with pork, the principle of zoonotic transmission through close contact with animal tissues applies to pork-specific viruses as well [125]. For instance, workers in pig farms and slaughterhouses have shown higher seroprevalence rates for HEV compared to the general population in many studies [126]. This highlights the occupational risk associated with frequent exposure to pigs and pork products. Furthermore, emerging viruses with pandemic potential, such as swine influenza virus variants, pose an ongoing threat to workers in close contact with pigs. The 2009 H1N1 influenza pandemic, which originated in swine, serves as a stark reminder of the potential for novel viral strains to emerge and spread rapidly from pigs to humans [127].

6. Conclusions

According to the information presented above, pork is associated with various viruses, including noroviruses, rotaviruses, astroviruses, adenoviruses, hepatitis A virus, hepatitis E virus, and enteroviruses. These viruses pose a threat to human health and significantly impact food safety. Despite the importance of this issue, routine studies in this area are not conducted, meaning that the actual level of risk remains unknown.

Further research is necessary to accurately estimate the prevalence of these viruses in meat samples and assess the associated risks. Despite the absence of clear evidence for zoonotic transmission, the potential for spillover to humans cannot be excluded. Effective monitoring, improved hygiene practices, and thorough cooking of pork products are crucial measures to mitigate the risks posed by these foodborne and zoonotic viruses.

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