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Microbial health hazards of recycling food waste as animal feed

Anita Dame-Korevaar[a,*], Iris J.M.M. Boumans[b], Adriaan F.G. Antonis[c], Ed van Klink[a], Evelien M. de Olde[b]

[a] Department of Epidemiology, Bioinformatics and Animal Models, Wageningen Bioveterinary Research, Wageningen University & Research, Houtribweg 39, 8221 RA Lelystad, the Netherlands
[b] Animal Production Systems group, Wageningen University & Research, P.O. Box 338, 6700 AH Wageningen, the Netherlands
[c] Department of Virology and Molecular Biology, Wageningen Bioveterinary Research, Wageningen University & Research, Houtribweg 39, 8221 RA Lelystad, the Netherlands

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ABSTRACT

The use of food waste as animal feed could contribute to a more circular and sustainable food production. Feeding swill (consumption phase food waste) however, is historically associated with disease transmission to animals and humans. The aim of this paper is to review the microbial health hazards of feeding swill to farm animals, with a focus on pigs and poultry. First, the current European food waste legislation is described. In literature 60 articles describing the hazards of feeding swill to pigs and poultry were identified. Most of the articles focus on viruses, mainly at the level of animal feed and animal-based food products. Articles describing bacterial hazards and also information on the microbial hazards on the level of kitchen and table waste and food consumption level were lacking. Described management factors related to swill feeding are factors such as herd size, management practices and biosecurity. This study shows that feeding kitchen and food waste to pigs and poultry includes various microbial health hazards. Many microbial hazards in animal feed can be overcome by adequate (heat) treatments, good facilities and strict regulations. However, also other hazards, such as non-infectious pathogens, physical and chemical hazards need more insight.

1. Introduction

In response to the increasing demand for food, specialised and large-scale animal and plant production systems have been developed (Steinfeld et al., 2006). Those systems are, however, associated with a high environmental impact through the emission of greenhouse gases, loss of biodiversity, and competition for land and water (Leip et al., 2015; Poore and Nemecek, 2018). To address those issues, a more optimised and circular food system is proposed that minimises the input of finite resources and stimulates the recycling of resources (De Boer and Van Ittersum, 2018; Jurgilevich et al., 2016). A circular approach implies that unavoidable by-products, such as food losses and food waste that cannot be reused as human food, should be recycled back into the food system to feed animals or to enrich the soil or fertilize crops (De Boer and Van Ittersum, 2018). Those inedible or unwanted products for humans could function as feed for livestock that can convert it into valuable animal products, such as meat, milk and eggs (De Boer and Van Ittersum, 2018).

Food waste occurs at various levels of the food system (e.g. at farm, processing or consumption level) and is estimated to be about 1.3 billion tonnes per year globally (Gustavsson et al., 2011). The largest share of waste occurs at the consumption phase, such as waste from households, restaurants and supermarkets. In the EU, for example, about 70% of food waste occurs at the consumption phase (Åsa Stenmarck et al., 2016). Historically, cooked kitchen and table waste, also referred to as “swill”, formed a main component of pig feed in Europe. Its use decreased after the Second World War when farm size increased and intensified, and simultaneously grain and soy became cheap and popular ingredients for pig diets (zu Ermgassen et al., 2016). Moreover, feeding food waste was limited due to risks of disease transmission.

Disease transmission can occur if contaminated food waste is not sufficiently heated before being fed to animals. In the past, feeding swill has caused severe animal disease outbreaks, including the outbreak of African swine fever (ASF) in the Netherlands in 1986 (Terpstra and Wensvoort, 1986) and foot and mouth disease (FMD) in the United Kingdom in 2001 (Davies, 2002). Feeding swill was therefore banned in these countries, followed by a ban across the EU in 2002 (European Commission, 2002; Ministerie van Landbouw Natuur en Voedselkwaliteit, 2003 and Ministerie van Landbouw Natuur en Voedselkwaliteit, 2018). Since then EU legislation prohibits the use of animal products, catering wastes and feeds that can cause intra-species recycling (i.e. cannibal-

* Corresponding author.
E-mail address: anita.dame@wur.nl (A. Dame-Korevaar).

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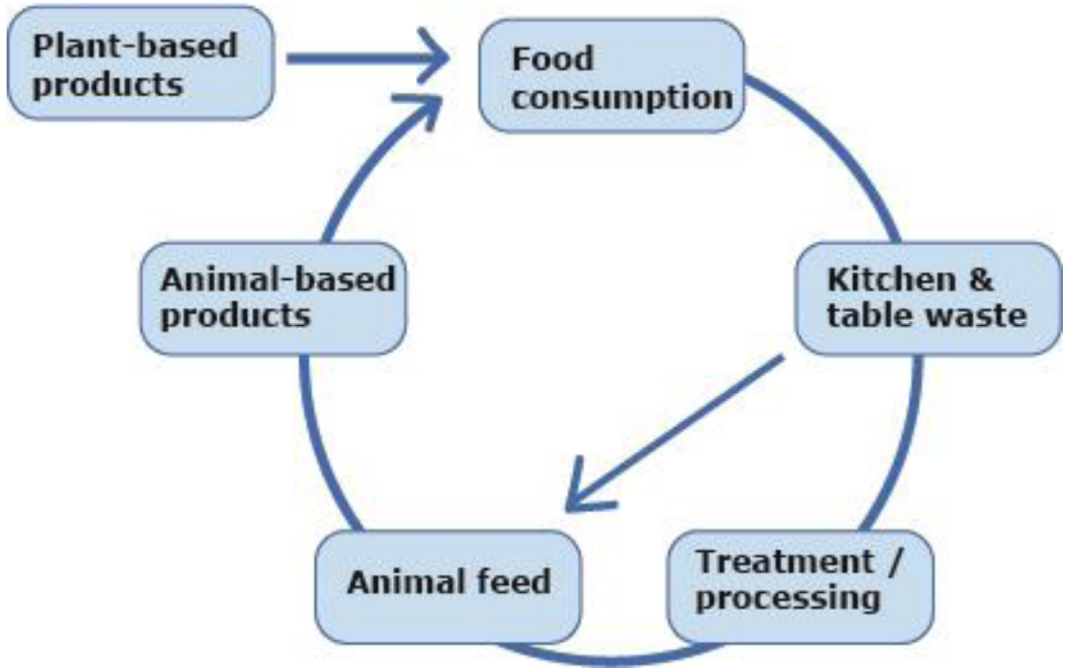

Fig. 1. Phases in the production and consumption of food and processing into animal feed.

ism), which includes most of the EU food waste (Zu Ermgassen et al., 2018).

Recently, however, the use of food waste as a low-cost and low environmental impact feed is being discussed again (e.g. Dou et al., 2018; zu Ermgassen et al., 2016). Legalisation of recycling food waste as animal feed could contribute to a more circular food system in the EU and could improve current sustainability issues, such as waste management, food security, resource use and environmental impact, without compromising meat quality or farm income (Dou et al., 2018; zu Ermgassen et al., 2016). A disadvantage of feeding swill, however, is the risk of disease transmission for both animals and humans. Food waste can contain various microbial and prionic agents that can cause diseases such as FMD, ASF, classical swine fever (CSF), salmonellosis, toxoplasmosis and bovine spongiform encephalopathy (BSE).

Theoretically, the microbial safety of feeding waste to animals should be sufficient when it is heated and handled properly (Dou et al., 2018). The use of heat-treated food waste is proven successful in countries such as Japan and South-Korea, where about 40–45% of food waste is reused as feed for livestock, such as pigs (Zu Ermgassen et al., 2018; zu Ermgassen et al., 2016). However, there is a risk when procedures are not sufficiently performed, as shown by a recent example in China where feeding (insufficiently heated) kitchen waste containing pig meat and slaughterhouse waste (dried pig blood) contributed to the further spread of ASF outbreak in pigs (Sur, 2019; Zhai et al., 2019). Furthermore, recent studies also indicate the risk of transmitting prion diseases by feeding ruminants food waste with cattle- and sheep-derived materials, in which biological activity of DNA might not be fully destroyed by normal heating methods (Chen et al., 2015). Those safety risks for animals and humans are not limited to only the treatment phase (Fig. 1) but can also occur through cross-contamination elsewhere in the system. Fig. 1 shows the different phases in the production and consumption of food, including the processing of kitchen and table waste into animal feed. In each of these phases, and between phases, cross contamination with microbial contaminants can pose a risk for the health of animals.

Since not only food waste but also by-products like human and animal excreta and compost are recycled in a circular food system, microbial contaminants can remain and accumulate in the system resulting in an increased risk of contamination. Not only microbial contaminants, but also chemical (e.g. heavy metals, dioxins, pesticides and microplastics) and physical (e.g. plastics, bones, packaging material) residues might be a risk (Dou et al., 2018; Pinotti et al., 2019; Tretola et al., 2017). While moving towards a more circular food system presents important environmental advantages and is increasingly adopted in policy (e.g. vision of the Dutch Ministry of Agriculture (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2018)), insight is needed in the health risks that might occur when feeding food waste to animals. An overview of those risks is needed for future strategic and practical decisions in the transformation towards a circular food system in the EU.

The aim of this paper is to review the microbial health hazards of consumption phase food waste (i.e. kitchen and table waste from households, hotels, restaurants and hospitals, often defined as “swill” (Uwizeye et al., 2019)) as feed for farm animals (Fig. 1). We focus on pigs and poultry as the main species to process these sources of food waste (van Hal et al., 2019). To provide understanding of what is currently allowed in terms of feeding food waste to farm animals, the next section describes current food waste legislation in the EU. Then we discuss various microbial (i.e. bacteria, viruses, fungi and parasites) hazards for animal health if swill is to be used again.

2. Food waste legislation

Before we describe the methods used to answer our research questions, we will give a brief overview of current legislation in the EU with regard to feeding food waste. As part of the EU plan on the Circular Economy, the EU launched guidelines to use food no longer intended for human consumption as feed for animals, without compromising public and animal health (European Commission, 2018). This section discusses which waste streams are currently allowed as animal feed and which are prohibited.

Legislation on using food products in animal feed is addressed in multiple regulations of the European Parliament and the European Council (Jędrejek et al., 2016; Aspevik et al., 2018). The European legislation distinguishes two categories of food waste: products that do not consist of, contain or are contaminated with products of animal origin, and products that do. The latter fall directly under the regulation on the use of animal by-products (Regulation 1069/2009 (European Parliament and Council, 2009). Products in the first category may become waste or be used as feed. Products from the food manufacturing process, such as sunflower seed expeller, wheat germ, sugar beet molasses, can be used in feed. Final products from manufacturing, wholesale or retailers do not meet the by-product criteria in the Waste Framework Directive and are considered as waste. These products may enter the feed chain as 'waste for recovery' under EU and national legislation (European Parliament and of the Council, 2008). The use of food wastes is only permitted when there is no risk of contamination with animal products demonstrated (zu Ermgassen et al., 2016).

Current legislation does allow the use of certain animal products including animal fats, egg and egg products and milk based products, provided the material is of EU origin and has undergone processing according to the food hygiene legislation (Luyckx et al., 2019). Moreover, with processing, fish and fishery products and non-ruminant meat are only allowed for aquaculture, pets and fur animals (Luyckx et al., 2019). To avoid spread of communicable diseases such as transmissible spongiform encephalopathies (TSE), through contaminated feed, animal by-products are divided into three categories linked to their origin and associated risks to public and animal health and the environment (European Commission, 2011; Aspevik et al., 2018). Category 1 by-products, or specified risk material (SRM) contains the highest risk material including materials that are considered a transmissible spongiform encephalopathies (TSE) risk, wild animals suspected of being infected with communicable diseases, and pet animals and experimental animals due to possibly high levels of veterinary drugs and residues. Category 2 by-products is also a high risk category and includes materials that are suspected of carrying disease agents, materials with an excess of drug residues, animals that died outside the food chain, and manure. Currently only category 3 by-products are allowed to be used as animal feed for certain specified categories of animals (companion animals, for example) and includes materials with a low risk including products that are fit for human consumption but not intended for humans including feathers, bones, eggs and domestic catering waste (Jędrejek et al., 2016). Regulation 1069/2009 furthermore prohibits the use of catering waste for feeding of farm animals other than fur animals, and the use of animal or fish protein in feed for the same species (other than fur animals). To avoid the risk of TSE, category 3 is further specified based on their origin (i.e. ruminants or non-ruminants) (European Parliament and European Council, 2001).

3. Methods

Swill is defined in various ways in scientific literature. To ensure that all relevant literature concerning microbial hazards related to swill feeding were selected, we included different descriptions of swill in our search terms, such as "food waste" and "kitchen waste".

Articles were selected using search term "swill" and "pig" or "poultry". For the complete search terms see appendix A. The search was done in Pubmed, between 15 October 2019 and 17 May 2021. No limitations were set on year of publication. Selection was done based on title and abstract and thereafter on full articles. Articles were included if hazards, defined as "an agent that has the potential to cause harm" (European Parliament and Council, 2002), and risks, defined as "likelihood of an adverse effect happening times the severity of its effects", associated with feeding swill to pigs and poultry were discussed. Relevant references mentioned in the articles were also included in the database. The papers included in the final database contained information on potential microbial hazards and risks associated with feeding swill to pig or poultry. Possible other factors, related to the association between swill feeding and microbial challenges, mentioned in the different articles are summarized in paragraph 4.3.

After having performed the selection of articles, the microbial hazards discussed in the included papers were classified on the basis of the type of animal and the microbial hazard discussed, and categorized according to their phase in the production and consumption of food and processing into animal feed as presented in Fig. 1: 1) kitchen & table waste (i.e. origin of swill), 2) treatment/processing, 3) animal feed, 4) animal-based food products or 5) food consumption. In the individual articles, often the definition of swill, i.e. the content and eventually treatment of swill, is unclear. Therefore, in our article we included the terminology as was mentioned in the original studies.

4. Results and discussion

The search "swill" and "pig" or "poultry" resulted in 82 articles. After selection of the articles, based on the criteria described in the previous paragraph, in total 60 unique articles were included (Fig. 2, Table 1). In the database 40 articles concerned pigs and 19 concerned poultry. The reason that pigs are more prominent in literature is probably because they historically have been fed on food waste and are well adapted to this feed. This might also have led to more swill related disease issues surfacing in the pig industry than in the poultry industry (Davies, 2002; Gogin et al., 2013; Sanchez-Vizcaino et al., 2013; Swayne and Beck, 2005; Terpstra and Wensvoort, 1986). Nevertheless, poultry and pigs are together the most likely species that will benefit from the use of food waste streams in their feed (van Hal et al., 2019). Therefore, it is relevant to assess risk of the use of food waste streams, and mitigation of such risks, as intensively in the poultry industry as in the pig industry.

Some of the selected articles included information about more than one microbial hazard. Most of the articles were about viruses (48), only 6 addressed mycotoxins, and 5 addressed parasites. No articles on bacterial hazards were found. The most likely reason for the prominent role of viruses in literature is that most large outbreaks of disease in both pigs and poultry, that were associated with swill feeding, were viral diseases with considerable impact (Davies, 2002; Gogin et al., 2013; Jurado et al., 2018). Many diseases resulting from bacterial, fungal or parasitic infections are quite often endemic. As a consequence, swill feeding will play a relatively minor role in the epidemiology of these diseases. Luyckx et al. (2019) did an expert solicitation on use of food waste for animal feed, in relation to the application of different treatment methods, i.e. heating, acidification and fermentation. They identified concerns about certain types of particularly spore forming bacteria, such as *Bacillus cereus* and *Clostridium* spp., and recommended attention to these issues in further development of processing methods.

Most selected articles addressed microbial hazards at the level of animal feed (38). Into other phases of the food cycle, as represented in Fig.1, there is considerably less research. Twenty one articles addressed animal-based food products, which includes articles on the contamination, presence or survival or possible methods of inactivation of a certain microbial hazard in animal products. Only one article was about the risks of swill feeding on the level of treatment/processing of swill. None of the included articles contained information at the level of kitchen & table waste (origin of swill) or on food consumption level. This is most likely associated with the fact that swill feeding has been prohibited in many countries, particularly in Europe, thus taking away the necessity to engage in research on this topic. Ten articles in the database were not categorized into one of the phases of the food cycle, but mentioned risk factors, such as management factors, that were associated with the practice of swill feeding and additional microbial challenges.

4.1. Hazards associated with swill feeding in pigs

In this paragraph the microbial hazards associated with swill feeding to pigs are included. Articles mentioning survival of pathogens in relation to potential contamination of pig products and swill are discussed in paragraph survival of viruses.

4.1.1. Viral hazards

Several viral hazards were mentioned in the literature. The hazards that were mentioned were mostly important notifiable diseases or dis-

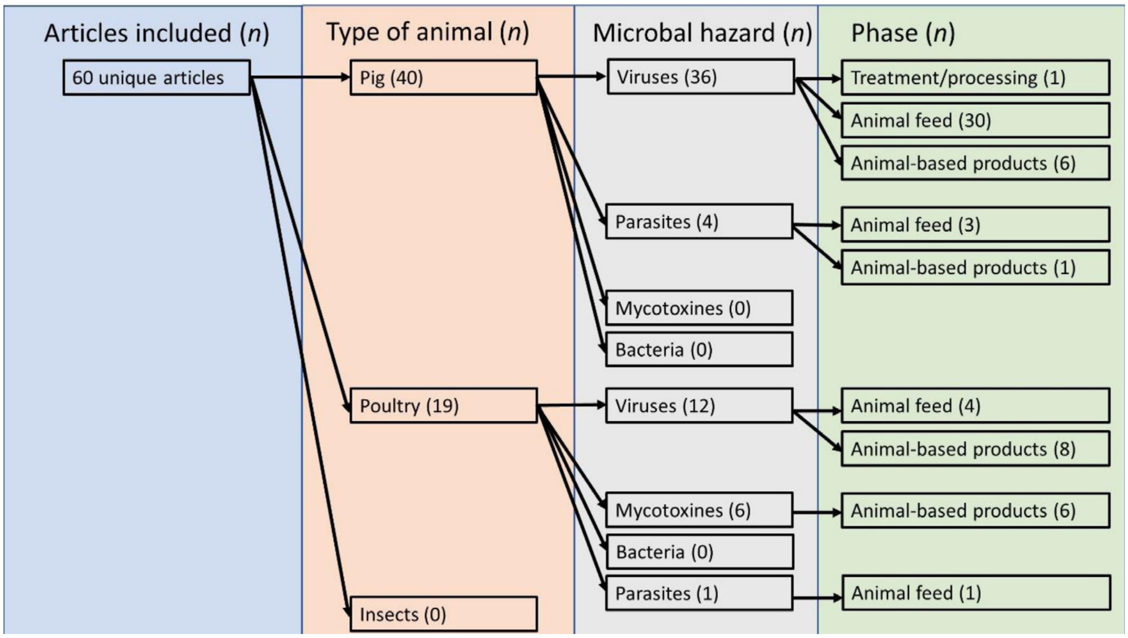

Fig. 2. Articles (n=60) included in the database, per type of animal, microbial hazard and phase in the production and consumption of food and processing into animal feed as presented in Fig. 1.

eases of great economic consequence: CSF, ASF, FMD, porcine reproductive and respiratory syndrome (PRRS), or had zoonotic potential: hepatitis E virus (HEV).

Analysis of CSF outbreaks in Germany between 1990 and 1998 showed that 23% of the 93 primary outbreaks were due to swill feeding (Fritzemeier et al., 2000). A risk analysis study estimating a low probability of introducing ASF/CSF in the United States (US) (Herrera-Ibata et al., 2017) identified swill feeding as a risk factor and suggested that swill feeding should be done in a controlled manner, including proper heat treatment, regulation e.g. using licensed facilities and controls in place (Broad Leib et al., 2016). The risk varied per state of the US and depended on the season. A study carried out in Bhutan including governmental and backyard pig farms showed that swill feeding increased the risk on testing seropositive for CSF (OR 2.25, 95% 1.10 – 4.99), indicating that infections are occurring in these herds and might be of concern for the risk of transmission. Similar to the risk analysis study from the US, Monger et al. suggest that cooking swill before feeding it to the pigs might reduce the chance of introduction of CSF virus (Monger et al., 2014).

The first and only outbreak of ASF in The Netherlands in 1986, occurred on a farm feeding uncooked swill to its fattening pigs (Terpstra and Wensvoort, 1986). Vergne et al. (2017) identified swill feeding as one of the drivers for spread of ASF in China. Other factors mentioned were people movements, imports of live pigs and pig products and the wild boar population. Also in South-Africa, Mongolia and China swill feeding practice was suggested as one of the potential mechanisms for the introduction of the ASF virus (Amar et al., 2021; Heilmann et al., 2020; Wu et al., 2020; Janse van Rensburg et al., 2020). In West Africa (Brown et al., 2018) and in Uganda (Nantima et al., 2015) swill feeding was identified as a prime cause of introduction after which spread took place mostly through pig movements. In Uganda, farmers were generally not aware that they were supposed to treat swill. Gogin et al. (2013) and Sanchez-Vizcaino et al. (2013) identified swill feeding as the main cause of introduction of ASF on the European continent in Georgia in 2007. Both swill feeding and illegal transports have been instrumental in spread across the Russian Federation. Jurado et al. (2018) emphasised, based on expert assessment, the necessity to enforce the Europe wide ban on swill feeding as an important biosecurity measure to prevent spread of ASF in European domestic pigs.

An Australian study showed that one of the most likely routes to introduce FMD in Australia is via importing and feeding FMD-contaminated meat (Hernandez-Jover et al., 2011). However, a risk assessment study in the same country (Hernández-Jover et al., 2016) aiming to define the risk of introduction and spread of FMD through large-scale and small-scale pig producers in Australia, showed that for all sectors the probability of exposure to FMD virus is very low. Importantly, the risk of infection by exposure via swill feeding was 10 to 100 times more likely than by exposure to infected feral pigs. In the Pacific Islands, swill feeding in smallholder and backyard pig farms (leftovers from restaurants without systematically boiling or cooking) was identified as risk factor for FMD along the pig market chain (Brioudes and Gummow (2016). The outbreak of FMD in the United Kingdom, Ireland, France and The Netherlands in 2001 started through swill feeding at a pig farm (Valarcher et al., 2008).

A cross-sectional study on HEV in India, where no regulations exist on the use of swill, including pigs fed with kitchen waste/swill and pigs fed with formulated heat-treated mixed feed showed that swill fed pigs had a significantly higher risk of being HEV RNA positive than non-swill fed pigs (OR 16.4, 95% CI 2.0 – 133.2). However, the seroprevalence of HEV was not different. Poor swill management and feeding practices in India could have been a factor for the higher HEV prevalence (Bansal et al., 2017). A Chinese study, including only a few farms, showed that the prevalence of anti-HEV antibodies in serum of pigs fed on only slightly heated kitchen waste was higher (87.1%) compared to pigs fed on complete (conventional pig) feed (53.1%) (Xiao et al., 2012).

Experiments have shown that horizontal transmission of Porcine Reproductive and Respiratory Syndrome (PRRS) by feeding infected meat to naive pigs is possible (van der Linden et al., 2003). The risk of occurrence of PRRS virus was higher if uncooked swill was fed (OR 3.0, 95% 1.3 – 6.6) compared to not feeding swill, whereas the risk on PPRS virus was not different if cooked swill was fed (1.6, 95% CI 0.9 – 3.0) in Vietnam (Truong and Gummow, 2014). As there are no regulations on swill feeding in Vietnam, the presence of meat in the waste fed to pigs could have been the source of PRRS virus infection. PRRS virus is

Table 1
Articles (*n*=60) included in the database, per type of animal, microbial hazard and phase in the production and consumption of food and processing into animal feed as presented in Fig. 1.

		Kitchen and table waste	Treatment/processing	Animal feed	Animal-based products	Food consumption
Microbial hazards of feeding swill to pigs						
CSF	Edwards, 2000			x		
	Farez and Morley, 1997			x		
	Fritzemeier et al., 2000			x		
	Herrera-Ibata et al., 2017			x		
	Jelsma et al., 2019				x	
	McKercher et al., 1987				x	
	Monger et al., 2014			x		
	Penrith et al., 2011;			x		
	Ribbens et al., 2004;			x		
	Vargas Teran et al., 2004			x		
	Weesendorp et al., 2008			x		
	Wijnker et al., 2008			x		
ASF	Amar et al., 2021			x		
	Brown et al., 2018			x		
	Gogin et al., 2013			x		
	Heilmann et al., 2020			x		
	Herrera-Ibata et al., 2017			x		
	Janse van Rensburg et al., 2020			x		
	Jurado et al., 2018			x		
	McKercher et al., 1987				x	
	Nantima et al., 2015			x		
	Petrini et al., 2019				x	
	Sanchez-Viscaino et al., 2013			x		
	Terpstra and Wensvoort, 1986			x		
	Vergne et al., 2017			x		
	Wu et al., 2020			x		
FMD	Brioudes and Gummow, 2016			x		
	Hernandez-Jover et al., 2011			x		
	Hernandez-Jover et al., 2016			x		
	McKercher et al., 1987				x	
	Valarcher et al., 2008			x		
PRRS	Hall and Neumann, 2015				x	
	Truong and Gummow, 2014		x	x		
	Van der Linden et al., 2003			x		
HEV	Bansal et al., 2017			x		
	Xiao et al., 2012			x		
Parasites	Corridan and Grey, 1969			x		
	Dubey et al., 2005				x	
	Foreyt, 2013			x		
	Van Knapen, 2000			x		
Microbial hazards of feeding swill to poultry						
AI	Brioudes and Gummow, 2016			x		
	Brown et al., 2008			x		
	Chmielewski and Swayne, 2011				x	
	Das et al., 2008				x	
	Harder et al., 2016				x	
	Swayne and Beck, 2005				x	
	Swayne, 2006				x	
	Thomas and Swayne, 2007				x	
	Thomas et al., 2008				x	
	Toffan et al., 2008			x		
ND	Abolnik, 2017			x		
	Alexander and Manvell, 2004				x	
Mycotoxines	Covaci et al., 2009				x	
	Pizzolato Montanha et al., 2018				x	
	Tangni et al., 2009				x	
	Van Overmeire et al., 2009a				x	
	Van Overmeire et al., 2009b				x	
	Waegeneers et al., 2009				x	
Toxoplasmosis	Braz et al., 2020			x		

rapidly inactivated by heat (Hall and Neumann, 2015). Hall and Neumann (2015) found a low probability of viable PRRS virus being present in pig carcasses, therefore importation of raw pork into PRRS virus-free countries remains hazardous.

Survival of viruses: The transmission of viruses via swill is partly depending on the survival of the viruses in the environment, e.g. in and on meat and carcasses, and the effect of treatment. In several articles included in the database the effect of certain treatments on survival of the virus is mentioned. For example, for CSF it is known that feeding uncooked swill can contribute to the transmission, because of the ability of the virus to persist in uncooked pork (i.e. the material has not been subjected to a cooking process specifically to prepare it for feeding to pigs, normally done on farm) (Penrith et al., 2011; Ribbens et al., 2004; Vargas Teran et al., 2004) and the detection of CSF virus in several processed meat products such as salami and ham (Farez and Morley, 1997). Transmission of CSF from contaminated sausage casings, treated with citrate and stored at 4 °C, to pigs was demonstrated in an experimental study (Wijnker et al., 2008). However, the survival of the

CSF virus in pig meat is variable and depends on the treatments used (Edwards, 2000; Wijnker et al., 2008; Jelsma et al., 2019).

Meat processing such as curing seems to inactivate infectivity for some viruses. Virus infectivity of ASF was not found after the process of dry curing uncooked salami, pork belly and loin, respectively 16, 60 and 83 days after processing (Petrini et al. (2019). The drop in pH to 5.0–5.8, which takes place early on in the curing process, did not seem to have any effect on virus persistence. Also after the process of curing in Parma ham, no infectivity was detected of CSF virus (after 189–313 days), ASF virus (after 300–309 days) and FMD virus (after 108–170 days) (McKercher et al., 1987). PRRS virus was rapidly inactivated by extensive heating, but this virus will survive in meat for extended periods at temperatures between −20 and −70 °C (Hall and Neumann, 2015).

Moreover, meat or carcasses can carry pathogens as a result of cross contamination, for example, due to contact with contaminated excreta during processing. CSF virus, for instance, can survive for 66 days (95% CI 16 – 272) in faeces and for 23 days (95% CI 1.9 – 283) in urine at a temperature of 5 °C (Weesendorp et al., 2008).

4.1.2. Other/non-viral hazards

Next to the viral challenges, a few articles mentioned the potential risk of parasite transmission through swill. *Trichinella spiralis*, causing Trichinellosis, can be transmitted when fresh, frozen or decomposing carcasses or meat scraps are fed to pigs (Foreyt, 2013). This parasite can be spread via infected and insufficiently cooked swill feed (Corridan and Gray, 1969; Van Knapen, 2000). Also *Toxoplasma gondii* can be present in pork meat (Dubey et al., 2005). None of the articles in the database contained information on bacterial or fungal hazards.

4.2. Hazards associated with swill feeding in poultry

In this paragraph the microbial hazards associated with swill feeding to poultry are included. Articles mentioning survival of pathogens in relation to potential contamination of poultry products are discussed in paragraph *Survival of viruses*.

4.2.1. Viral hazards

The viral challenges that were identified in the selected literature were: avian influenza (AI) and Newcastle disease (ND).

Experiments showed that highly pathogenic AI (HPAI) virus can be present in poultry meat and eggs (Brown et al., 2008; Chmielewski and Swayne, 2011; Das et al., 2008; Swayne and Beck, 2005) and feeding this meat to other birds could lead to transmission of HPAI (Brown et al., 2008). However, low pathogenic AI (LPAI) virus could not be transferred via infected meat (Swayne and Beck, 2005) and experimental transmission of HPAI to naive turkeys failed (Toffan et al., 2008). Collection of uncooked poultry waste thrown in a bin to be fed to pigs, where poultry had access to, was identified in a risk pathway analysis as a risk factor for HPAI along the poultry market chain in the Pacific Islands (Brioudes and Gummow, 2016).

For ND the import of infected poultry products has been suggested as source of introduction in South-Africa (Abolnik, 2017).

Survival of viruses: AI in meat can be inactivated with thermal inactivation (70 °C core temperature, according to kitchen standards) assuming that properly cooked poultry meat and eggs do not pose a risk of exposure (Harder et al., 2016; Swayne, 2006; Thomas et al., 2008; Thomas and Swayne, 2007).

In an experiment where poultry meat was spiked with ND-virus and subsequently heated to 60, 65, 70, 74 and 80 °C, Alexander and Manvell (2004) found that the virus was readily inactivated from 65 °C onwards. The time it took to reduce the virus activity by one log10 (i.e. a 90% reduction in activity) was estimated at respectively 120 s, 82 s, 40 s and 29 s for the four highest temperature categories.

4.2.2. Other/non-viral hazards

Next to the viral challenges, a few articles mentioned other microbial challenges in poultry. Feeding food scraps increased the risk on seroprevalence of *Toxoplasma gondii* in free range chickens in Brazil (OR 1.6, 95% CI 1.13-2.28). This might be related to the consumption habit of the owners: feeding animals with leftover meat and raw viscera (Braz et al., 2020). Mycotoxins can be present in animal feed, due to contamination of feed ingredients, and can consequently end up in animal meat or meat products (Pizzolato Montanha et al., 2018). However, a Belgian study investigating eggs produced by kitchen waste-fed chickens in small-scale farms could not correlate the levels of mycotoxins and non-pathogenic hazards as dioxins, trace elements and chemicals in kitchen waste with the levels in eggs, indicating that kitchen waste is not an important contamination source for these substances in eggs (Covaci et al., 2009; Tangni et al., 2009; Van Overmeire et al., 2009a; Van Overmeire et al., 2009b; Waegeneers et al., 2009). None of the included articles contained information on bacterial hazards.

There may be other microbial hazards in animals and animal products, that apparently do not seem to be associated with swill or not have been studied. Pathogens carrying antimicrobial resistance can be found on meat, for example in pork and poultry meat (Murphy et al., 2018; Perez-Rodriguez and Mercanoglu Taban, 2019) as well as in egg shells (Álvarez-Fernandez et al., 2012; Mezhoud et al., 2016) and resistance can be transmitted between commensal microbiota and pathogens (Quintieri et al., 2019). Salmonellas and campylobacters may also be found in pig and poultry products. Furthermore, it is striking that there apparently is little to no attention for e.g. heat stable toxins produced by micro-organisms that might be transferred through (heat treated) swill, such as enterotoxin b (STb), produced by certain *Escherichia coli* bacteria (Dubreuil, 2018). Dou et al. (2018) mention analyses for toxins they found in a few publications, but do not mention any results. Salemdeeb et al. (2017) mention human toxicity of non-carcinogenic substances in feed, such as zinc.

4.3. Management factors associated with swill feeding

The use of swill (generally poorly defined in most literature, but consumption phase food waste (Uwizeye et al., 2019) can be considered a useful definition) to feed animals may be related to factors such as herd size, management practices and biosecurity. Currently, swill feeding happens generally more often in small-scale backyard farming (Gogin et al., 2013; Hernandez-Jover et al., 2011; Sanchez-Vizcaino et al., 2013). Hernandez-Jover et al. (2011) define swill as illegally introduced meat products, subsequently fed to pigs. Such farms might have a lower biosecurity level, less veterinary care and less understanding of (the risks of) swill-feeding (Hernández-Jover et al., 2016; (Sanchez-Vizcaino et al., 2013). A review on the transmission of CSF revealed different biosecurity clusters, in which the lowest biosecurity cluster included mainly small size farms, with management characteristics such as swill feeding and pigs pasturing (Ribbens et al., 2008). Swill feeding is often related to poor or complete lack of biosecurity as studied at Australian exhibitions, where feeding of swill, defined as illegally imported meat or meat products, occurs allowing introduction and transmission of exotic diseases, normally not occurring in Australia (Cha et al., 2009). A survey following an HPAI outbreak in backyard poultry holdings in Bhutan also showed that farm housing and management practices are generally of a low biosecurity standard, and include the feeding of food scraps to the birds (Tenzin et al., 2017). The authors recommended education of farmers on this. Interviews with pig producers in Australia have also shown a lack of knowledge on the risks of feeding of swill (meat scraps, prohibited substances) for introduction and transmission of exotic diseases as potential risk (Schembri et al., 2006; Schembri et al., 2010). Not only small-scale backyard farms, however, are at risk from swill feeding. During the ASF outbreak in the Netherlands in 1986 it was concluded that swill feeding (then legally, all be it after a cooking process, which would be done on the farm) mostly happened in specialised fattening farms in sparsely populated pig regions (Terpstra and Wensvoort, 1986). In the farm involved in this outbreak, food waste from hospitals, retirement homes and restaurants was fed uncooked to the pigs, which, even then, was illegal.

4.4. Beyond the microbial hazards of swill feeding

In this review we mainly focused on the microbial hazards of swill feeding. However, also physical and chemical hazards might play a role (Dou et al., 2018; Pinotti et al., 2019; Tretola et al., 2017). Also, if swill is to be used as feed component, the nutrient composition and potential deficiencies will become a relevant question point. Consumption phase food waste is suggested to be a good replacement for (parts of) conventional pig feeds, although more accurate information about nutrient content, variability and bioavailability (e.g. of phosphorus) is required (Dou et al., 2018). There does not seem to be any information on cross-contamination between swill that has and has not been (heat) treated.

In addition to the apparent risk of transmission of high impact (non-endemic) infectious animal diseases, there is a potential theoretical threat for human health. Parasitic, bacterial and viral diseases can be introduced in animal populations by feeding contaminated and insufficiently processed food waste. Though some of the hazards included in the review are zoonotic (e.g. hepatitis E, avian influenza, parasites), risks for human health were not within the scope of this review.

Also other species are considered promising in recycling food waste, such as insects and fish. Insects are considered as alternative sources of protein both for human and for animal nutrition. For animal feed, black soldier fly larvae as protein source is being considered in feeds for pigs and poultry, while also being seen as an effective recycling mechanism for organic waste (Tomberlin and van Huis, 2020). Fish might be the most efficient species in recycling waste into food products (Van Hal et al., 2020, manuscript in preparation). At present, however, using swill for production of insects or feeding swill to fish is not allowed. It may well be that this changes in the future. Also in these species, understanding of risk of potential pathogen transmission to humans or animals is important (Haenen et al., 2013, Joosten et al., 2020).

Re-introduction of swill as animal feed will clearly require the adherence to stringent preconditions regarding the treatment and storage of the material and the way it is fed (Dou et al., 2018; zu Ermgassen et al., 2016).

Proper heat treatment would be sufficient to inactivate viruses and kill other micro-organisms (Brioudes and Gummow, 2016; Hall and Neumann, 2015). An explanation of three categories of heat treatment methods (i.e. wet-based, dry-based and ensiling/fermentation treatment) can be found in the article of Dou et al. (2018). The microbial safety of feeding properly treated swill to animals has been demonstrated in several studies and shown to work in practice in South Korea (Dou et al., 2018; Zu Ermgassen et al., 2016b). Historically, before it was banned in the EU, swill was cooked on farm (Terpstra and Wensvoort, 1986), which made controlling the process and managing the risk difficult, and mistakes easily be made. The current outbreaks of ASF show that containing the risk constituted by feeding swill is a challenge. It is therefore likely that both the treatment option on farm and logistic issues related to the location of treatment and the distribution of the processed product if not processed on farm will require attention. In the framework of renewed interest in circular agriculture, where recycling food waste would be a logical and key element, it would be recommended to further investigate on the most appropriate ways of treatment of these waste streams to make them suitable for animal feed, overcoming the risks as presented in this paper.

5. Conclusions

Feeding consumption phase food waste to pigs and poultry includes various microbial health hazards. In literature several risks for viruses in both pigs and poultry are identified, as well as parasites (pigs) and mycotoxins (poultry). Most attention in literature is on the animal feed and animal-based food products, but less on risks in other phases of the food production and consumption cycle (i.e. treatment/processing, food consumption and kitchen and table waste), when processing food waste into animal feed. Adequate heat treatment of swill would be sufficient to inactivate viruses and kill other micro-organisms, but more insight is needed also in other hazards, such as non-infectious pathogens, physical and chemical contaminants.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Complete search terms, including synonyms.

swill and poultry/pig: swill OR "food scraps" OR "kitchen waste" OR "kitchen refuse" OR “food waste” AND birds OR poultry OR broiler OR broilers OR "laying hen" OR "laying hens" OR farm OR farms OR breeder OR "parent stock" OR flock OR chicken OR pullet OR swine OR porcine OR pig OR piglet OR sow OR boar

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