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Review

Feeding food losses and waste to pigs and poultry: Implications for feed quality and production

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ABSTRACT

Feeding food losses and food waste (FLW) to livestock can reduce the environmental impact of livestock production, but practical implications for feed quality and feed production systems are currently unclear. The aim of this paper is to address the potential implications for pigs and poultry feeding systems when FLW would (fully or partly) replace conventional ingredients of animal feed within the European Union. FLW streams, such as (prohibited) animal-based foods or household waste, constitute a substantial and valuable part of available FLW. Feeding FLW, however, also includes challenges regarding the (anti-) nutritional value, physical and sensory characteristics, and contamination risks of animal feed. Mixing various FLW streams can be a solution for the large variability in nutritional value and physical characteristics, but more knowledge is needed about the various properties of FLW streams, best handling and processing methods, validated analysis techniques and inclusion levels in animal feeds. We discuss the scale and location of processing FLW, as well as the required infrastructure for dealing with supply and demand. Different approaches may be taken to increase the use of FLW into livestock diets and transition into a sustainable and circular food system. How this could be best implemented will likely be a trade-off between costs and benefits. It should be discussed both among direct users and within the wider society which costs and risks are acceptable.

1. Introduction

The need to transform our food systems to avoid exceeding the Earth's biophysical limit and produce food with respect for humans and animals is widely recognized (Jurgilevich et al., 2016). Future food systems need to produce healthy and nutritious food in a climate-smart, nature-inclusive and resilient way, while also respecting the needs of humans and animals (Leip et al., 2015; Dawkins, 2017; Poore and Nemecek, 2018).

A circular food system is increasingly seen as a solution to produce food while respecting the Earth's biophysical limits. Circular food systems ought to safeguard natural resources (e.g. healthy soils), encourage regenerative practices (restorative fishing), prevent food losses and waste, and stimulate the reuse and recycling of inevitable losses or waste in a way that adds the highest possible value to the system (de Boer and van Ittersum, 2018; Muscat et al., 2021). Livestock in a circular food system would not consume any biomass that is edible by humans, such as grains, but mainly convert food losses and food waste (FLW) from arable land (e.g. crop residues, losses and waste from food production) and grass resources into valuable food (de Boer and van Ittersum, 2018). This approach would largely decouple livestock feed from arable land, implying that the competition for land between food and feed, also referred to as food-feed competition, is largely avoided. Currently, as much as 40% of all global arable land is used to produce high-quality feed for livestock, of which almost half is used for monogastric animals (Mottet et al., 2017). Monogastric animals are mainly broilers, laying hens and pigs, which are kept in industrial housing systems. Their feed consists for more than 50% of grains (Mottet et al., 2017). Removing these human edible ingredients from the diets of poultry and pigs by FLW, can contribute substantially to the global human food

List of abbreviations: ANF, Anti-nutritional factors; EU, European Union; FFP, Former food products; FLW, Food losses and food waste; PAP, Processed animal proteins.

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supply while at the same time reducing the environmental impact of the entire food system (van Zanten et al., 2018).

FLW originates from the farm (e.g. crop residues that remain on the land), during transport, storage, processing and sales of food products, or from households at the consumption stage. Globally, about one-third of all agricultural products (1.3 billion tonnes of food) is lost or wasted (Stenmarck et al., 2016). While it should be a first priority to prevent FLW, some of it will likely be unavoidable and may be fed to livestock. The interest in feeding FLW to livestock has been growing in recent years. The European Commission adopted, for example, a circular economy action plan in 2015, to prevent FLW along the food production chain and to stimulate more sustainable production, including reuse of FLW as animal feed (EC, 2015). Previously banned use of FLW in the EU, due to risks of disease transmission, are being discussed again. This includes the use of swill, which are cooked FLW from human consumption (Zu Ermgassen et al., 2016a, 2016b; Dou et al., 2018) and the use of processed animal proteins (PAP) from poultry and pigs (EFPRA, 2021b). Legislation must be adapted to allow and stimulate further use of FLW in livestock feed in the EU. Recently, a proposal to amend Annex IV in Regulation (EC) No 999/2001 was adopted to allow again feeding PAP of pigs to poultry and vice versa. The use of PAP within species and PAP derived from cattle remains banned.

Replacing conventional feed ingredients with FLW, however, can negatively affect the feed quality and the way it must be provided to animals. Although several studies reviewed the use of FLW in livestock feed and mentioned aspects of feed quality, such as major nutritional values (e.g. Zu Ermgassen et al., 2016b; Dou et al., 2018; Rajeh et al., 2021), a systematic overview of important feed quality properties of FLW is still missing. Such consequences on feed quality and feed production systems are currently unclear, but it can have a considerable effect on behaviour, biological functioning and health of animals, for instance, due to nutritional quality, physical characteristics or contamination risks of feed. Furthermore, the use of FLW as feed ingredients may require other production conditions of both food and livestock to guarantee availability and safety of feed, and consequently, food production. Hence, insight in these consequences is very important, but has received limited attention in scientific studies so far, in our opinion.

Therefore, the aim of this paper is to address the potential implications of feeding FLW to pigs and poultry, either exclusively or to a (much) larger extent than currently being practiced in conventional systems in the EU. We focus on the EU, because this is in line with the action plan (EC, 2015), and on pigs and poultry, because in intensive systems these animals are currently being fed on a diet that largely consists of human-edible grains. Furthermore, as omnivores, pigs and poultry are expected to be the best suited to process FLW. We first outline the current use and potential of using FLW in monogastric diets, and then systematically discuss various properties and possible risks when using FLW to replace conventional ingredients in line with a circular food systems approach. We examine how using FLW could affect important characteristics of feed quality for pigs and poultry, and what production conditions it would require. We finally discuss different approaches and sustainability challenges in a transition to feeding FLW in a more circular food system.

2. Which food losses and waste can be used in livestock feed?

2.1. *Definition of food losses, waste and leftovers*

The terms food losses, food waste and food leftovers are often used interchangeably, while related terms such as co-products, by-products, side or waste streams are also being used. Without a clear definition, using these terms more or less interchangeably may lead to ambiguity in what is meant by the terms ‘food loss’ and ‘waste’ in the concept of FLW in relation to the objective of this paper. For clarity, we define food waste – as overarching term - in line with Östergren et al. (2014) as “any food, and [human] inedible parts of food, removed from the food supply chain to be recovered or disposed (including composted, crops ploughed in/not harvested, anaerobic digestion, bio-energy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea)”. In this definition, and in our paper, we use the term ‘food’ to refer exclusively to nutritive consumables for humans, while the term ‘feed’ is used to refer to what is suited for consumption by animals, in particular livestock. As such, food waste can occur due to any cause, removal-method, as well as at any stage of the production chain (Fig. 1). The terms ‘food losses’ and ‘food waste’ are used to distinguish waste at the early or late supply chain stages. Losses at the production, post-harvesting, and (primary) processing stages can be referred to as ‘food losses’, while at the retail and consumer stage it is referred to as ‘food waste’ (Parfitt et al., 2010). In the latter case, food wasted due to overcooking, -preparing or -serving may be referred to as ‘food leftovers’ or ‘swill’ (Parfitt et al., 2010). Other forms of food leftovers are ‘former food products’ which refer to foods manufactured in full compliance with EU food laws, but that are wasted due to practical, logistic or processing reasons (e.g. mislabelling, mispackaging, prototype products, non-compliant brand requirements). Finally, although terms like ‘co-products’ or ‘by-products’ are occasionally used to indicate food losses or food waste, it should be noted that the terms themselves only identify secondary products derived from the production of a principal product or service (Dictionary, 2021). Hence, while some co-products and by-products may not continue to be used as food in the food production chain, they cannot be considered food waste by definition. In this paper, we focus on all food losses and food waste (FLW) occurring along the food supply chain.

2.2. *Origin and amount of food losses and waste*

The total amount of FLW not currently used in livestock feed or biobased products is estimated at one-fifth of total EU production or 88 million tonnes per year (Åsa Stenmarck et al., 2016). Most of this FLW comes from household consumption (53%), followed by processing and packaging of food (19%), retail and distribution processes including food service, wholesale, logistics and markets (17%), and primary production, including (post)harvest handling and storage (11%) (Stenmarck et al., 2016). From the total amount of FLW in the EU, annually about 100 million tonnes, only 5% is currently converted into animal feed (according to the European Former Foodstuff Processors Association (EFFPA), 2017, cited in Čolović et al., 2019a). Animal meat and fat wasted at the EU rendering industry (e.g. slaughterhouses and food producing plants) accounts for ~18 million tonnes per year, of which only ~2.5 million tonnes (~13.9%) are processed into pet food and animal feed (EFPRA, 2021a).

2.3. *Current use of FLW in livestock feed*

FLW can be of plant-based or animal-based origin. Currently, mainly plant-based FLW are structurally and on large scale used in animal feed. They generally originate from the food-processing industry and consist of refusals and residuals from bakeries and confectionaries, forming part of the category former food products (FFP; Table 1). Feeding animal-based FLW (e.g. slaughterhouse waste), on the other hand, is associated with pathogenic risks and has resulted in various disease outbreaks in the past (e.g. bovine spongiform encephalopathy and classical swine fever) (Jędrejek et al., 2016). Therefore, FFP containing or being contaminated with meat, fish or shellfish (with a few exceptions), as well as waste from catering and kitchen facilities is not allowed in the EU for use in livestock feed (Jędrejek et al., 2016). As a result only a limited part of animal-based FLW is currently allowed in livestock feed in the EU, and if so, only after being processed and considered safe from risk of contamination (Table 1).

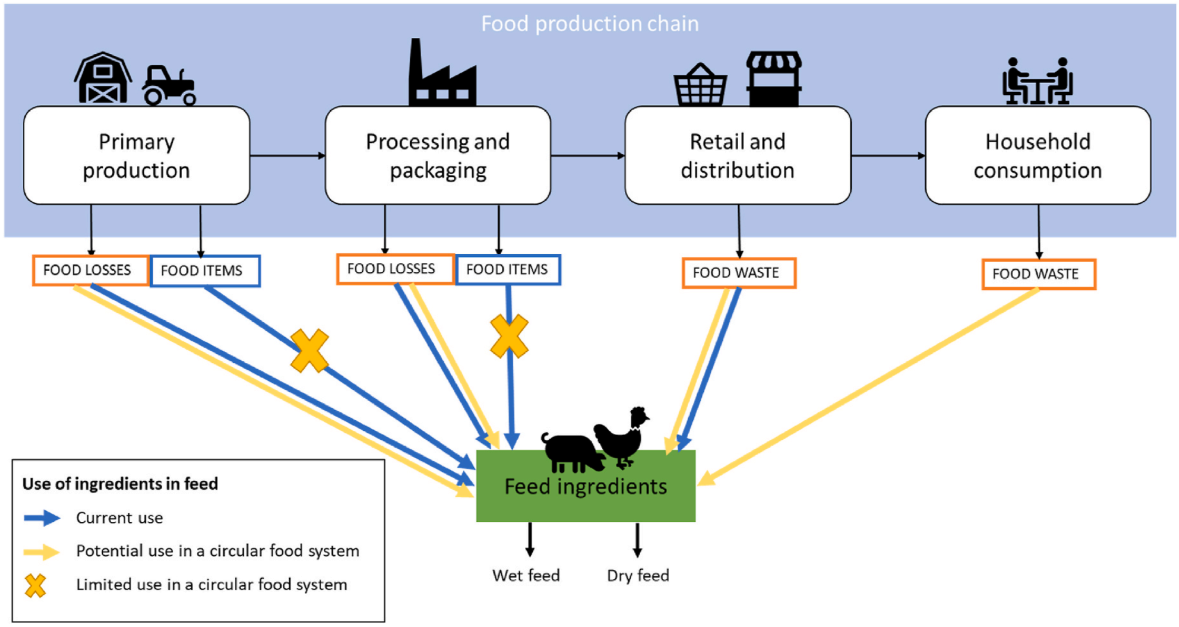

Fig. 1. Outline of current (blue arrows) and potential (yellow arrows) use of human edible food items, and food losses and waste (FLW) resulting from the food supply chain to feed livestock. Following the principles of a circular food system, in which production of animal feed is based on FLW, while human-edible food items are no longer used as animal feed (yellow cross).

2.4. Potential future type and availability of food losses and waste

Currently, it is not clear how much of FLW would actually be suitable and available for feed production. Zu Ermgassen et al. (2016b) estimated that potentially 39% of FLW could be recycled into animal feed (15 million tonnes from manufacturing, 2 million tonnes from retail, 6 million tonnes from catering and 17 million tonnes from household waste). The dry matter content of these FLW is estimated to be between 20 and 30% (Zu Ermgassen et al., 2016b).

The use of plant-based FLW can be increased by including more human-inedible co-products from the food industry, and by making more efficient use of human-inedible co-products of the biofuel and vegetable-oil industries (Boland et al., 2013). Some plant-based FLW have a poor nutritional value and may be rich in undesirable anti-nutritional factors (ANF). But they can also be rich in other nutrients or bioactive compounds (Čolović et al., 2019a). Grape by-products from wine making, for example, are rich in polyphenols that are considered to be ANF for monogastrics. Such grape by-products also have antioxidant and antimicrobial properties and can reduce the need for vitamin E supplementation in feed for monogastric animals (Brenes et al., 2016). In addition, sources such as grass leaves and leaves from tuber production (e.g. sugar beet, cassava) might be used in the future to extract RuBisCo (i.e. the enzyme ribulose biphosphate carboxylase), which is a highly abundant plant-based protein that may be suitable for feed or food production. It is estimated that global sugar beet production, for example, accounts for a loss of about 3 million metric tonnes of plant-based RuBisCo protein in leaves (Boland et al., 2013).

Although generally prohibited as feed for livestock, animal-based or animal-contaminated FLW such as slaughterhouse waste, FFP, and food waste from human consumption have high potential as feed ingredients. These sources are mostly protein and/or energy-dense, and offer good opportunities as feed for livestock (Jędrejek et al., 2016; Dou et al., 2018; Luciano et al., 2020). Recently, the EU reapproved (through amendments to Annex IV of EU Regulation (EC) No 999/2001) the use of PAP derived from poultry and farmed insects in pig feed, as well as the use of PAP derived from pigs and farmed insects in poultry feed. Also collagen and gelatine derived from ruminants is allowed again to feed to pigs and poultry. While PAP provides a great potential as alternative protein source for livestock, regulations require dedicated transport, processing and storage facilities, and/or strict cleaning procedures for the handling and processing of PAP into livestock feed (Amendments to Annex IV of EU Regulation (EC) No. 999/2001). These strict requirements are in place to avoid cross-contamination and intra-species recycling. They may, however, also hamper an immediate (re-)adoption of PAP as animal feed source by industry.

In addition to animal-based FLW and PAP, household waste can be regarded an interesting feed source. Household waste makes up the largest portion (53%) of FLW (Stenmarck et al., 2016) and as a feed source it has a high potential to increase the production of animal-based protein food derived from livestock (van Hal, 2020). Although the feeding of this so-called swill is allowed in countries like Japan and South Korea, its use as animal feed in the EU is limited. Current EU legislation allows the use of swill as feed only when no risk of contamination with meat products can be demonstrated. When the use of swill is optimised under the current legislative regime in the EU, only a small amount of grains currently used in pig feed could be substituted (Zu Ermgassen et al., 2016b). However, following the example of countries like Japan and South Korea, relaxed EU legislation could allow swill feeding to make up for as much as 20% of the current dry matter in pig feed (equivalent to 8.8 million tonnes of grains)(Zu Ermgassen et al., 2016b).

3. Feeding food losses and waste: implications for feed quality

Feed quality is determined by the properties of the feed ingredients (Fig. 2). These properties determine potential inclusion levels in feed and adequate feed formulation. In this section we discuss these properties and potential implications when using FLW as ingredients.

3.1. Nutritional value of food losses and waste

Overall, the nutritional content and qualities of different types of FLW may differ considerably. Plant-based FLW, for example, can be sources of protein, carbohydrates, essential fatty acids, antioxidants, pigments and other fibres for livestock (Čolović et al., 2019a). Animal-based FLW may provide good sources of protein and essential

Table 1
Types of food losses and food waste (FLW), and their use in livestock feed.

Type of FLW	Examples	Current use in livestock feed	Potential future use in livestock feed
Plant-based FLW	• Vegetables left on land, e.g. roots and pulses.[a] • Processing by-products, e.g. brewer's grains, rice bran, wheat middlings, oilseed meals and citrus pulp.[b] • Former food products (FFP), e.g. biscuits, bread, chocolate and pasta.[c]	Food losses in primary production, during processing and packaging, in retail and distribution are partly used.[a,b,c,d] Catering and kitchen waste products are not allowed for use in animal feed in the EU.[d]	More use of products with poor nutritional value, and more extended and efficient use of co-products of biofuel and food industries.[b,f] More use of FFP.[c]
(Contaminated with) Animal-based FLW	• Animal residues during slaughter and processing of animals, e.g. fat trims, viscera, blood, bones, feathers and skins.[d] • FFP, e.g. products that contain meat, fish, animal fat, milk or eggs.[d] • A mixture of food waste from food service places or households.	Use is largely restricted by EU legislation. Only animal-based products, such as animal fats, fish oils, porcine gelatine, milk and eggs, that (after processing) are considered safe from risk of contamination are allowed for feed use. Recently, processed animal proteins (PAP) have been allowed again (though intra species recycling is still banned).[e] Catering and kitchen waste products are not allowed for use in animal feed in the EU.[d]	Increased use of slaughterhouse waste, FFP[d] and waste produced in the stage of human consumption (swill).[g]

[a] Hartikainen et al. (2017); Hartikainen et al. (2018).
[b] Čolović et al. (2019a).
[c] Giromini et al. (2017).
[d] Jędrejek et al. (2016).
[e] EFPRA (2021a).
[f] Boland et al. (2013).
[g] Zu Ermgassen et al. (2016b).

amino acids, as well as fats, vitamins, and minerals, especially calcium and phosphorus, and even carbohydrates in case of certain dairy products (Arvanitoyannis and Ladas, 2008; Jędrejek et al., 2016). FFP are considered sources of carbohydrates, free sugars and fats. In general, FFP have a high nutritional value in terms of energy and overall digestibility (Giromini et al., 2017; Luciano et al., 2020). FLW from the human consumption-stage contain high levels of major nutrients, such as protein, fibre, fat and carbohydrates (see review Dou et al., 2018).

Besides variation between types of FLW, the nutritional content and quality can vary between batches, especially when FLW batches are available in small quantities or when they rapidly deteriorate (Salami et al., 2019). Plant-based FLW from industrial processing, for example, usually has a higher nutritional value than crop residues left on the fields, but this can rapidly decrease depending on the preceding processes during the production of the primary product and preservation methods afterwards (Salami et al., 2019). Moreover, FLW can be susceptible to fermentation, microbial (mould) development and deterioration leading to nutrient reduction and alterations. To retain nutrient values and to increase shelf life, methods to preserve FLW should therefore be developed (Salami et al., 2019).

When focussing on variation in nutrient content, a Danish study compared co-products from vegetable food and agro-industries (i.e. brewer's spent grain, pea hull, seed residue (rye grass), potato pulp, sugar beet pulp and pectin residue). They found that the relative range of variation in macronutrients was mostly similar to that of conventional ingredients such as barley and wheat in other Scandinavian studies (Serena and Knudsen, 2007). For animal-based FLW (e.g. blood meal, chicken by-product meal and feather meal) (Kerr et al., 2017) and FFP (e.g. a mix of FLW from the food industry) (Giromini et al., 2017) a small to moderate variation between samples was found in nutritional value and digestibility. The variation in these products, however, seems quite predictable and therefore manageable in feed formulations (Giromini et al., 2017; Kerr et al., 2017; Tretola et al., 2019). By contrast, knowledge on the variability in nutrient content and digestibility of food waste from human consumption is limited, as feed composition tables for livestock generally not include food products for humans (e.g. NRC, 1994; NRC, 2012; CVB, 2021). Hence, there is a need to extend current feed composition tables to make better use of the nutritional content and variation of FLW streams. This also applies to micronutrients like phosphorus, which is an important nutrient for pigs and poultry, and on which data is lacking (Dou et al., 2018).

When focussing on the formulation of livestock diets, information on the digestibility and bioavailability of nutrients is essential. Digestibility varies between FLW. Animal-based products are usually highly digestible sources of nutrients for livestock (Jędrejek et al., 2016). This is also true for items that have been subjected to industrial processing and drying, as heat treatment may improve nutrient composition and digestibility (Almeida et al., 2014). The nutritional value of FLW may be increased by processing and by adding feed additives. For example, dried distillers grains had a higher protein content and digestibility after modifying the traditional co-production process of biofuel production by separating endosperm of the grain before fermentation (Boland et al., 2013). Moreover, processing can increase the nutritional value of FLW by reducing or eradicating ANF. This can be done through physical (e.g. dehulling), heat (e.g. extrusion or cooking) or biological (e.g. enzyme supplementation) treatments (Jezierny et al., 2010). In the latter case, enzymes such as phytases, xylanases and β-glucanases are added to monogastric diets to reduce the impact of specific components (Tona et al., 2018). The presence of high concentrations of other (chemical) substances like salt, however, may hamper the inclusion of certain FLW in animal diets (Georganas et al., 2020). Nevertheless, like in conventional diet formulation, the nutritional quality of FLW-rich diets may be handled by setting maximum inclusions rates, by blending FLW sources and by including additives like enzymes, vitamins, minerals and synthetic amino acids, to make up for imbalances in the nutrient or amino acid profiles of the feed.

Overall, inclusion rates of certain FLW in livestock feeds, as well as homogenisation through mixing of several FLW, can be used to deal with variation in the nutritional value of FLW items. Also, making use of rapid analysis methods such as Near Infrared Spectroscopy (Berzaghi and Riovanto, 2009; Prananto et al., 2020) and in vitro techniques (Wang and Zijlstra, 2018) to quickly determine the nutritional composition and bioavailability of nutrients in FLW could be of interest. However, the validity of such techniques need to be established, by developing accurate calibration databases for example (Wang and Zijlstra, 2018). Despite various options to deal with variation in nutrient content and quality of FLW, there is a need to extend current feed composition tables with data on different FLW streams to facilitate their use in livestock diets.

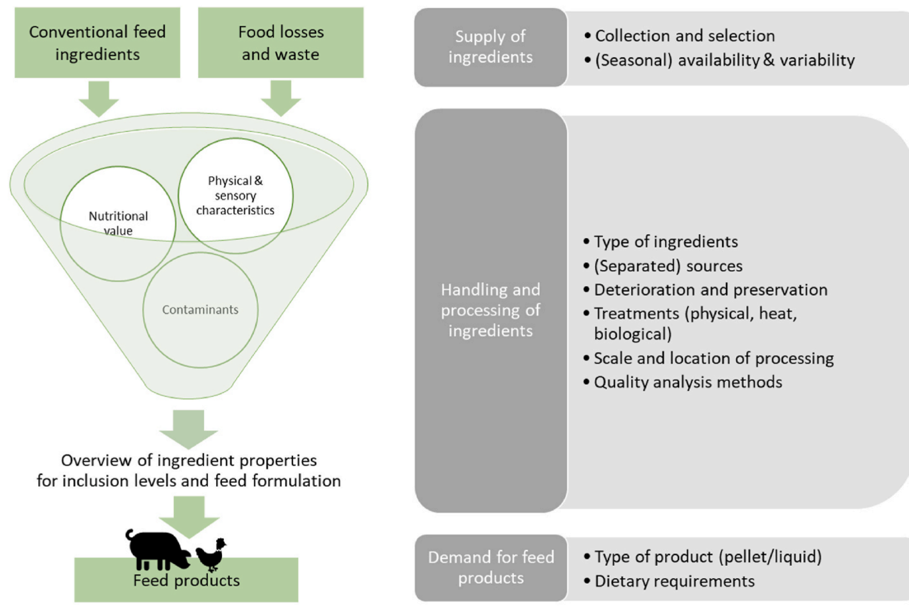

Fig. 2. Overview of main factors influencing the quality of livestock feed, as determined by the ingredients, their properties, inclusion levels and feed formulation (green boxes, left side). This depends on supply, handling and processing of feed ingredients, and on the demand for feed products (grey boxes, right side).

3.2. Physical and sensory characteristics

To optimise the use of FLW in livestock diets also the physical and sensory characteristics need to be considered. In this respect, especially challenges exist regarding fibre and moisture content of some FLW.

Dietary fibre, a low digestible carbohydrate, is important for development and functioning of the gastro-intestinal tract (Wenk, 2001). For monogastric animals, the proportion of (bulky, insoluble) fibre in the diet is generally limited as a high fibre content can reduce digestibility and feed intake (Lindberg, 2014; Celi et al., 2017; Tona et al., 2018). Plant-based FLW may contain many fibres, which restricts their use in animal feed. However, in combination with other ingredients high-fibre ingredients can still be used in moderate amounts, depending on the species (San Martin et al., 2016). By-products from brewing, such as dried brewers' grains, for example, have a high fibre content and are therefore of less value for poultry (Čolović et al., 2019a). For restricted-fed gestating sows, however, increased fibre in feed may reduce hunger, prolong satiety and reduce aggressive and stereotypic behaviours (Danielsen and Vestergaard, 2001; D'Eath et al., 2009).

Water is important for the osmo-regulatory balance of the body and can be provided with and in addition to feed. FLW from human consumption are generally high in water content (Dou et al., 2018). This is also true for many plant-based FLW. They have a moisture content that is often higher than 80% (Čolović et al., 2019a). When adequately treated and quickly fed to animals, FLW can be fed as liquid feeds with a moisture content of up to 80% (Dou et al., 2018). Especially pigs are known for being able to consume liquid feeds (Boland et al., 2013). Fermented products in liquid feeds may have prebiotic effects in pigs and this can be beneficial to reduce bacterial contamination (Farzan et al., 2006). FLW with a high water content can also be mixed with dry products or with ingredients that are low in water content (Čolović et al., 2019a). Although drying may be costly, it could reduce transportation costs and prolong storage possibilities.

The importance of sensory characteristics of feed for farm animals, such as colour, odour, texture and taste has often been underestimated (Favreau-Peigne et al., 2013; Nielsen et al., 2015). Sensory characteristics affect palatability and feed intake (Favreau-Peigne et al., 2013). The sensory characteristics of FLW are poorly known in literature. Some FLW have a bitter taste or unappealing flavour. The use of FLW in animal feed requires knowledge about the final palatability of these feeds and the need of sensory additives. Phytogenic feed additives, such as essential oils and herbs, can enhance or mask some flavours and increase the palatability of feed (Steiner and Syed, 2015). Compared to other mammals and poultry, pigs seem to have a highly-developed taste acuity, and therefore, may be more sensitive to the taste of feed (Steiner and Syed, 2015; Roura and Fu, 2017; Niknafs and Roura, 2018).

A final aspect to consider when producing dry feed from FLW is the impact on pellet quality. Current pellets include ingredients that result in strong pellets. Their replacement with FLW may decrease pellet strength. Processing FLW to reduce particle size (Wondra et al., 1995) or adding ingredients that improve binding (Thomas et al., 1998) may be important for production of good pellets.

In general, inclusion rates of FLW may have to deal with fibre and water content of certain FLW items. More knowledge about the sensory characteristics of FLW is needed. Also the effect of FLW on pellet quality must be taken into account, if the production of dry feed is desirable.

3.3. Contamination risks

Like in conventional feed ingredients, contamination risks exist related to the processing and feeding of FLW. These can be of physical, biological or chemical nature, and can result from any cause, removal-method or at any stage of the food production chain. As presented by Thakali and MacRae (2021), recycling FLW can lead to contamination and recycling of contaminants in various stages of a circular food system (Fig. 3). These authors considered the recycling of FLW for soil replenishment rather than for animal feed. Nevertheless, the potential contamination sources are similar. At each stage in a circular food system, contaminants can enter and be passed on to the next stage.

Physical contamination with packaging remnants, such as plastics, paper and aluminium foils may occur in FLW. The risks of such contaminations may be higher for FLW from human consumption (e.g. FFP, swill) considering the generally higher packaging rate compared to agricultural crops or FLW items. Studies by Tretola et al. (2017) and van Raamsdonk et al. (2011), however, showed that physical rates of contamination of FFP generally stayed below the accepted limit of 0.15% weight concentration (>90% of the cases) and were not higher than 0.71%, indicating a limited (but not zero) risk of physical contamination when feeding FFP.

Biological contamination hazards, through viruses, bacteria, fungi

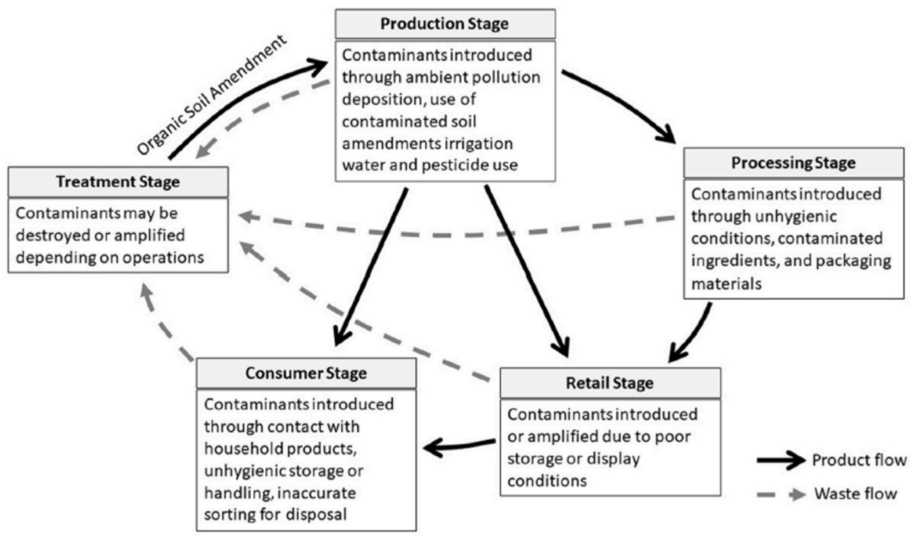

Fig. 3. Potential contamination and recycling of contaminants in different stages of a circular food system. Figure as presented by Thakali and MacRae (2021) and licensed under CC BY-NC-ND 4.0.

and protozoa, can occur in FLW. For example, when not fed or preserved adequately and in time, it can result in pathogen proliferation and spoilage of most types of FLW. Feeding animal-based FLW may also result in more specific biological risks. The protozoa *Trichinella spiralis*, for example, can be transmitted when infected animal tissue is fed to animals (Foreyt, 2013). This is also true for viruses, such as porcine epidemic diarrhoea virus (Dee et al., 2014; Trudeau et al., 2017) or classical swine fever (Edwards, 2000). In general, the risk of biological hazards can be limited when FLW are adequately processed and (heat) treated (Dou et al., 2018; Dame-Korevaar et al., 2021). Historic disease outbreaks in Europe, however, also showed the existence of biological contamination risks when feed was not adequately processed. Therefore, adequate control is required in processing of FLW for inclusion in animal feed.

In terms of chemical contamination, through industrial and agricultural chemicals and heavy metals, hazards for FLW and conventional feed ingredients are expected to be similar. Increased risks for FLW could include substances, such as heavy metals and dioxin, due to cross contamination with other waste types (e.g. household and garden waste) but information about these risks is limited (Dou et al., 2018). For FLW derived from the retail and consumer stage, a study by Garcia et al. (2005) showed that restaurant and household waste contained lead, cadmium, dioxin, furan and PCBs, sometimes exceeding minimum levels stated in EU regulation (EC, 2002). These contaminations proposedly occurred due to cross contamination with inorganic material (e.g. packaging, sand) in case of lead and cadmium, and overheating in case of dioxin and PCBs (Garcia et al. (2005)).

In general, contamination risks may be limited when FLW are adequately handled and processed (Dou et al., 2018). Physical contamination and cross contamination may be reduced using separation methods (e.g. sieving, air fractionation). Biological contamination may be avoided or reduced through adequate application of conserving methods (e.g. by temperature and/or pH control, and addition of conservatives). Moreover, cross contamination may be reduced by installing separate collection and handling routes. However, as with reducing or solving mycotoxin contaminations in feedstuffs (Čolović et al., 2019b), no single method may be effective or efficient in dealing with every possible contamination risk. Proper handling and adequate regulatory and control measures are therefore essential when dealing with contamination risks related to feeding FLW to livestock (Dou et al., 2018).

3.4. Substitution rates and production levels when feeding FLW

Similar to current diet formulation, the feasibility to design diets for pigs and poultry including or solely containing FLW depends on the capacity of the feed ingredients to meet the dietary requirements of the animals. These requirements are determined by the animals' stage of life (e.g. pregnancy and lactation stage), health status and environmental factors (like the ambient temperature), the production target of the farmer and animal welfare requirements. Current legislation can influence or restrict the degrees of freedom the feed producer (or farmer) has to include FLW in livestock feed. As such, the level of inclusion is determined by the dietary demands and the ability of allowed FLW to meet those.

Pig and poultry diets generally contain high quality feed ingredients to improve performance (e.g., increasing feed efficiency, production rates and product quality). When focussing on these performance indicators, feeding FLW to pigs and poultry does not seem to affect feed conversion efficiency in general (Zu Ermgassen et al., 2016b). Similar feed efficiencies were reported when pigs and poultry were fed diets including up to 50% FLW, as compared to when fed a commercial diet (Rajeh et al., 2021). Also, while absolute growth rates may be affected by feeding FLW depending on the amount of FLW inclusion, the effects on meat quality were found to be limited (Zu Ermgassen et al., 2016b).

When considering the performance of livestock from a food systems perspective, indicators such as the (human-edible) protein conversion ratio, and land-use ratio may be of more interest to consider than the traditional indicator of dry-matter based feed efficiency (van Zanten et al., 2016; Hennessy et al., 2021). These metrics evaluate the net contribution of livestock to the food system, in terms of overall land-use or protein production. For pigs and poultry fed a commercial diet, the (human-edible) protein conversion ratios and land-use ratios are generally shown to be greater than 1, meaning respectively that these animals consume more (human-edible) protein than they produce, and that the land on which their feed is grown could have yielded more human-edible protein when used for crop production for humans (Wilkinson, 2011; Ertl et al., 2016; van Zanten et al., 2016; Hennessy et al., 2021). Considering that FLW are generally not suitable for human consumption and thus not driving land-use, their inclusion in diets may help monogastrics to become net contributors to the food system. Based on literature studies, the study of Zu Ermgassen et al. (2016b) has shown that increasing the proportion of FLW in pig diets linearly decreases the amount of land needed to produce 1 kg of pork compared to pigs fed conventional diets.

Hence, as for conventional feed ingredients, the inclusion rate of FLW in pig and poultry diets depends on the capacity of FLW to meet the various dietary requirements. While growth rates may reduce, the feed efficiency and meat quality do not need to be affected by including FLW. Other performance indicators (e.g. protein conversion rate and land-use ratio), which take into account the net contribution of livestock to the food system, emphasise the potential of monogastric livestock to produce high-quality animal sourced food based on human-inedible FLW.

4. Conditions for feeding FLW

In this section we discuss how feed production might have to change when we want to use FLW as ingredients in the diets of pigs and poultry.

4.1. Scale and location

The scale and location of processing plays an important role in dealing with challenges when using FLW in livestock feed, as posed by the (variable) availability and variability in nutrient content, and by the physical characteristics and contamination hazards. To answer the question on what kind of scale and location FLW can be best processed, the infrastructure in South-Korea as described by Zu Ermgassen et al. (2016b); Dou et al. (2018) could serve as an example. Two types of FLW supply chains are generally conceived. FLW that is regarded as safe for use as feed can be transported directly from the source of origin to the farm. The other route takes FLW through processing plants that accommodate the collection, treatment and storage of FLW before being transported to the farm. The former route may be referred to as decentralised and on-farm handling, while the latter may be seen as centralised handling.

On-farm handling can be beneficial to shorten the time between feed production and feed provision. This is especially relevant when FLW have a high deterioration rate, which may complicate transport, processing and storage, and may also include a higher risk for pathogen development and spoilage (Čolović et al., 2019a). FLW that vary greatly in nutritional value and that are not consistent available may complicate the direct use on-farm and on small or decentralised scale. Farmers will likely depend on listed average values of feed ingredients to deal with fluctuations in nutritional value (Serena and Knudsen, 2007). However, affordable, rapid analysis methods such as Near Infrared Spectroscopy (see section 3.1; Prananto et al., 2020) have been developed to enable the farmer to determine the nutritional value of ingredients and to deal with variation. A downside of on-farm processing FLW is an increased risk of insufficient heating or evaluation of FLW streams, resulting in safety and health issues. Illegal feeding of uncooked FLW to pigs has been suspected to be the cause of a foot-and-mouth disease outbreak in the past (Zu Ermgassen et al., 2016b).

Large scale and centralised facilities to collect, sort and process FLW can be beneficial to create homogenised batches of livestock feed (Dou et al., 2018). Those facilities are also expected to substantially reduce risks and costs. Storage of FLW might be needed to deal with (seasonal) availability. The production of dry feed can increase shelf life of feed and preserve nutrients, while it is also easier to transport over long distances (Zu Ermgassen et al., 2016b; Dou et al., 2018). Furthermore, treatment may also affect nutrient values and physical characteristics (Dou et al., 2018). A study in Japan showed that large scale processing of FLW can benefit the production efficiency of converting FLW into livestock feed (Nakaishi and Takayabu, 2022).

FLW differ in dry matter content. Facilities for wet feed processing may be located on-farm, where swill (heat-treated FLW) can be fed directly to animals. Facilities for producing dry FLW may be located nearby urban cities, where waste can be collected where it originates. Food waste collection and processing facilities may be set up and controlled by local governments and/or private contractors to ensure that feed quality and safety standards are maintained.

4.2. Cooperation for supply and demand

The availability in terms of volume and consistency of FLW will affect the ability to include them in feed and to produce the required amount of feed over a period of time. A sufficient and consistent supply will require cooperation between FLW generators, processors, and farmers to align supply and demand. FLW generators might need additional incentives to stimulate them to supply FLW to feed processors, such as high costs for disposal of waste via incinerators, and feed processors might need subsidies to increase the use of FLW as feed ingredients (Nakaishi and Takayabu, 2022). As discussed earlier, cooperation could be on small scale in case of on-farm or regional handling, but also on larger scale in case of centralised handling. Currently, cooperation exists between feed, and the manufacturing and retail industry as some FFP (e.g. bread and bakery waste) are already used in compound feeds for example. This cooperation could be extended for both plant-based (e.g. leaves) and animal-based FLW (e.g. PAP). For alternative systems that, for example, connect arable farmers, animal farmers and consumers, new forms of cooperation need to be set up. Generators of currently prohibited catering and household food waste might cooperate on small and regional scale with local farmers or feed producers, but their waste might also be collected more communally and transported to centralised facilities. Many FLW generators at the end of the food supply chain (e.g. households and restaurants) likely have small and maybe inconsistent streams of food waste. To deal with this, new infrastructure to collect, select and process these streams into adequate volumes of a safe product is then necessary. Improved separation of FLW by generators, especially those at the end of the supply chain, is important to improve quality and production efficiency of FLW (Nakaishi and Takayabu, 2022).

5. Final considerations

5.1. Incremental and transformational approach towards circular food systems

The use of FLW for livestock fits well within a circular food system. A change towards such a system could be incremental or transformational. An incremental change means that (parts of) existing farming systems may be changed in small steps without making fundamental changes to the system, whereas a transformational change includes a system-wide change and altered paradigms and values (Termeer et al., 2017). An example of a possible incremental-change scenario includes specialised intensive farming systems similar to current conventional farms, in which only (part of the) conventional feed is replaced with feed produced from FLW. FLW in this scenario could be included in the diet like other ingredients and turned, for example, in to a more or less regular dry compound (pelleted) feed that can be transported over a long distance. By contrast, a transformational change includes a holistic approach to more drastically transform the system. In a circular system, the role of livestock changes from solely producing animal-based food products to upcycling FLW streams into food products (de Boer and van Ittersum, 2018). An example of a transformational change is the development of alternative farming systems, based on regional opportunities and tackling multiple issues at once (e.g. de Boer et al., 2020). Systems may be developed, for instance, to connect nutrient flows between urban areas and surrounding agricultural areas. Livestock can be kept on the (arable) land or in the region where FLW, such as crop residues (or grass lands) become available. These systems may include outdoor housing and livestock breeds that are better able to deal with variability and reduced feed quality of FLW and less controlled housing conditions.

Hence, in the incremental approach to using FLW in a circular food system, FLW replaces current feed ingredients in (dry) compound feed without requiring substantial changes in current feed production processes or housing of livestock. The transformational approach entails a more fundamental redesign of the food system including FLW handling and feeding practises.

5.2. Economic and social sustainability challenges

The environmental benefit of replacing current (human-edible) ingredients of livestock feed with FLW has been shown extensively. It reduces the environmental impact directly (Salemdeeb et al., 2017) and it also reduces feed-food competition (van Hal et al., 2019b). Feeding FLW should, however, also be economically viable and socially acceptable.

Feed constitutes a relatively large economic cost in livestock production systems, representing the most important production cost in the EU with up to 57% of the farm gate value of poultry and up to 29% in the case of pigs in 2019 (FEFAC, 2021). Use of low-cost feed items could benefit farm profitability. FLW are expected to have a lower price than conventional ingredients. However, the costs for collection and processing may be high(er). Processing FFP, for example, may take a lot of manual labour even though machinery for unpacking some items exist. Centralised and large-scale facilities are expected to substantially reduce costs and improve efficiency. Furthermore, feeding FLW can also reduce growth rates of animals and thereby increase housing and labour costs per unit of product. However, in Japan feeding FLW to pigs has shown to be profitable (Zu Ermgassen et al., 2016b). Incentives that could stimulate lower prices for FLW and premium prices for animal products (e.g. via certification) may support the economic viability of using FLW in livestock feed (Zu Ermgassen et al., 2016b; Nakaishi and Takayabu, 2022). Another benefit would be to reduce the dependency on imported animal-feed ingredients (Sugiura et al., 2009) and fluctuating prices.

Social concerns about using FLW may relate to animal welfare, human safety and social acceptance of food produced from waste. Implications for animal welfare are currently unclear. Feed from FLW may, in theory, have a similar variation in nutritional quality, physical characteristics and contamination hazards compared to conventional feed. However, issues regarding current legislation, safe processing and variation in availability need to be dealt with. For example, while plant-based FLW are generally considered safe and widely accepted (Salami et al., 2019), this is not the case for animal-based FLW (Zu Ermgassen et al., 2018). In the UK, however, more than 75% of farmers and other stakeholders strongly support re-allowed use of swill in pig feed (Zu Ermgassen et al., 2018). That study also showed that communication to consumers is important to deal with multiple concerns, such as the safety of feed, disease outbreaks and meat taste quality for consumers. This stresses the importance of public communication to generate social support for feeding FLW to livestock.

In a future circular food system, the amount of animal-based products available for human consumption will be determined by the availability of resources that do not initiate food-feed competition. As such, the production of animal-based food will depend on the availability of FLW as a resource, and no longer on production maximalisation or consumer demand. Animal production will therefore be limited. Moreover, the share of livestock products available may differ from our current consumption pattern in such a scenario (e.g. more fish and milk production), as shown by van Hal et al. (2019a). Inevitably, the share of plant-based food in human diets will need to increase. In a circular food system, consumers would furthermore need to shift to diets that are more healthy, less wasteful and do not contribute to transgression of planetary boundaries (e.g. greenhouse gas emissions, eutrophication, acidification, biodiversity loss). Such a change in human food consumption will, in turn, change the type and availability of FLW for livestock feed production. As a consequence, livestock production will depend on resource availability rather than being a main driver for resource (i.e. livestock feed) production and land use.

Besides feeding FLW to livestock, a transition to a circular food system may result in other changes in current livestock production systems, such as housing conditions and manure management systems. This could bring opportunities to improve animal welfare in these systems, for example via reduced stocking densities, more time spent on feeding and exploration, varied diets, and more cognitively-stimulating environments. Moreover, while the risks for reduced animal welfare might be limited when animals are fed FLW compared to conventional feeds, there is a substantial risk that FLW will be incorporated in current systems in a way that it does not lead to any improvement in welfare, and this should be examined in more detail as much knowledge about this is still lacking.

6. Concluding remarks

Feeding FLW to monogastric livestock such as pigs and poultry may have benefits for the efficiency and sustainability of the overall food system, but considerations, opportunities and ways forward may vary, and are in part not yet sufficiently clear. The use of FLW as livestock feed, as envisioned in a circular food system, shows potential because of the utilisation of currently unused FLW streams. This is in line with studies that reviewed the feasibility of FLW use in livestock feed, indicating that it seems to be a viable solution (e.g. Zu Ermgassen et al., 2016b; Dou et al., 2018; Rajeh et al., 2021).

The present study shows that both plant-based FLW and animal-based FLW have potential to be utilised. This includes FLW that are currently legally allowed, such as more use of FFP, plant products with poor nutritional value, and more extended and efficient use of plant-based co-products of the biofuel and food industries. It also includes currently prohibited use of animal-based FLW streams, such as slaughterhouse waste and waste from human consumption, which is a substantial part of all FLW.

FLW sources within those streams, however, vary largely. We have shown that feeding FLW includes feed-quality challenges regarding the (anti-)nutritional value, physical characteristics and sensory characteristics, which partly can be overcome by mixing various FLW streams. Moreover, current legislation and contamination risks provide additional challenges to the processing of FLW into livestock feed. To overcome these, more knowledge is needed about the nutritional value of some FLW streams and about best handling and processing methods. This also requires performance indicators from a food systems perspective, such as land-use ratio, which also take the contribution of livestock to the food system into account. Future studies should address the characteristics of FLW streams, variation in nutrient content and quality of FLW, best handling and processing methods, validated analysis techniques and inclusion levels in animal feeds.

Furthermore, to match supply and demand, and to deal with the collection, transport and processing of FLW in livestock feed a new feed-production infrastructure may be required. In theory, the infrastructure can based on regional cooperation and on-farm handling, whereby on-farm facilities may benefit the feeding of wet FLW items due to short distance and time before feeding. However, large scale and centralised facilities are probably needed to meet feed safety requirements. Such facilities can also have the benefits of scale to deal with variation in and preservation of FLW and may be better able to turn FLW into an affordable dry feed that has a longer shelf-life and can be transported over long distances. A change in EU legislation is needed to increase the availability of valuable FLW streams. Also governmental support through policies and incentives that stimulate the recycling of FLW are important (Nakaishi and Takayabu, 2022).

From a sustainability perspective, the benefits for the environment of using FLW as livestock feed has been shown, but economic viability still has to be explored. Processing of FLW can be costly, and potential gains in the future can only be obtained through a profitable production in the present. Also social challenges should be dealt with, such as impact on animal welfare, human safety and social acceptance. Future research should address these issues.

In the future, different approaches may be taken to increase the use of FLW into livestock diets and aid the circular transition. This approach will affect how FLW will be implemented in livestock feed and what the impact will be on pigs and poultry production systems. An incremental approach, whereby FLW streams replace conventional ingredients in compound feed of current systems, may have limited impact on current systems. A transformational approach, whereby livestock production depends on resources availability and consumption patterns, however, could require a more holistic change in the design of livestock and food systems. How use of FLW, and to what extent, could be best implemented in Europe will likely be a trade-off between costs and benefits. It should ultimately be decided upon by direct users and within the wider society which risks that generate costs are acceptable.

Author contributions

Iris Boumans: Conceptualization; Investigation; Writing - original draft; Writing – review & editing; Funding acquisition. **Marijke Schop**: Investigation; Writing – review & editing. **Marc Bracke**: Conceptualization; Writing - original draft; Writing – review & editing; Funding acquisition. **Imke de Boer**: Writing – review & editing. **Walter Gerrits**: Writing – review & editing. **Eddie Bokkers**: Conceptualization; Writing - original draft; Writing – review & editing; Funding acquisition.

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Data availability

No data was used for the research described in the article.

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