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Review

New approaches for safe use of food by-products and biowaste in the feed production chain

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A R T I C L E I N F O

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A B S T R A C T

Reuse or recycling are some of the essential retention options recognised in circular economy approaches. An attempt to embed the linear feed and food production chain in the general concepts of sustainability and circular economy revealed common elements as well as principally different issues between feed/food and non-food strategies. Regrading of former food products as feed ingredients is an important, if not essential, development in reducing large volumes of biowaste, and to achieve a footprint as small as possible for animal husbandry. An analysis of legal requirements provides opportunities as well as legal restrictions for reusing former food as feed. The main focus is on European Union legislation, since this system ranges among the most strict legal frameworks globally. The specific issues include feed and food safety, possible adverse effects of strict loop closing, the frame of the biological background and legal requirements. Dedicated concepts are developed for reaching solutions.

Feed and food safety covers four domains; including biology (e.g. prions, viruses), chemical compounds (e.g. pesticides, antibiotics, heavy metals, dioxins), microbiology (pathogenic bacteria and viruses, zoonoses), and physical objects (e.g. microparticles, packaging material). Physical hazards should receive extensive attention for the frequent presence of packaging material in former food products.

Legislation should allow and encourage innovations and technologies for regrading of by-products of the feed and food production chain. The WISE principle (Witfull, Indicative, Societal supportive, Enforceable) for legal developments should be used for optimising the relationship between the legal framework, assurance of feed safety, and support of necessary innovations. Biological principles will add considerably to the concept of circular bioeconomy.

Examples with different backgrounds will be presented and discussed. Technological innovations for upgrading biowaste and former food products will result in suitable feed ingredients. The evolutionary distance between animals and their biological needs should be part of the design of strategies and of the legislative process. The requirement of circularity for production and usage loops should be applied diversely. The approach of food webs as found in nature should be explored for feed and food production. Genetic distance among species in loops or webs can be used as guidance for route diversification.

1. Introduction

Agriculture in the current era is challenged by two major incentives: minimization of the ecological footprint and maximization of the food security for the global human population. In both cases, a broad interpretation should be applied for these issues. Food production includes the feed production chain, and it should be subjected to safety for a large diversity of chemical and physical compounds, hygiene requirements and to sufficient nutrition. The ecological footprint differs widely among the different types, procedures and geographic regions of food production. Livestock husbandry ranges among the most disputed production chains of human food because of the large ecological footprint, and for the production of waste, including greenhouse gasses, manure and slaughter by-products (Van Kernebeek et al., 2016; Springmann et al., 2018). At the same time, cattle husbandry is for a range of cases the most obvious way of land use, most notably for marginal regions which are predominantly suitable for vegetable biomass production by grasses (Squires et al., 2018).

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An option is to connect both issues, by converting the by-products of food production with a major share in the ecological footprint to valuable feed products (ladder of Moerman; Waarts et al., 2011). Waste reduction is one of the measures used to improve the sustainability of the food production (Springmann et al., 2018). This option is a basic principle for the initiatives to achieve a circular bioeconomy as far as food production is at stake (European Commission, 2008).

Circularity in food production systems is just one example of the general requirement to make a transition towards a circular economy in general. The goal of the European Union's (EU) plan is to achieve that "a circular economy will reduce pressure on natural resources and will create sustainable growth and jobs" (http://ec.europa.eu/environment/circular-economy/index_en.htm). "Waste" is a commodity that does not exist in nature. Literally every type of material is recycled or reused in one of the many existing natural nutrient cycles. This principle was recognised in the concepts of industrial ecology (Frosch, 1992; Geng and Coté, 2002). Human societies are increasingly separated from the natural environment in the sense that the residual materials of human activities would not automatically be reintroduced in natural cycles (Brundtland, 1987: page 8). These limitations resulted in the introduction of the term "waste" in European Union (EU) legislation as a by-product of a range of activities. The feed and food production chain takes a specific position for the explicit requirement of maintaining food and feed safety (Pinotti et al., 2021). This is effectuated by a complicated set of EU legal requirements and limitations, which prevents certain options for reuse or remanufacturing of by-products of the food production chain, most notably those of animal origin. Several epidemics have caused to prevent the use of a range of these by-products in feed production. The use of catering waste (swill) as feed ingredient is considered an important route of infection with classical swine fever (CSF), in combination with other routes such as contact with other (wild) animals, secretions and excretions, mucus and skin contacts, transport vehicles, and artificial insemination (Ribbens et al., 2004; Anonymous, 2009). The virus causing foot and mouth disease (FMD) is assumed to be contained in bone marrow. Among other factors, meat and bone meal and swill can act as vector for transmitting FMD (Paton et al., 2009; Hagenaars et al., 2011). Accumulation of chemical compounds, especially those with a high lipophility, can result from installing short loops in order to reach the modern desire for economic circularity. Dioxins are an example of a family of chemical compounds with a high accumulation hazard (Hoogenboom et al., 2015; Malisch, 2017). These examples show that strict circularity of animal by-products can pose higher risk levels, an issue recognised in current EU legislation by installing strict prohibitions for reuse. Other non-EU legal systems implemented alternative solutions to prevent such higher risk levels (Shurson, 2020). Therefore, biological laws and principles will be presented and discussed for being a more robust and globally relevant framework.

This paper will explore the differences between the food and non-food production strategies for sustainability by means of the evaluation of key factors. Emphasis will be given to the use of a range of by-products or residual materials from food production as feed ingredient. The first part of this paper will focus on the evaluation of several EU legal restrictions for the reuse of by-products resulting from livestock husbandry, including mixture of materials including animal by-products, since the EU legislation range among the most severe legal systems globally existing. Biologically-driven prospects and opportunities will be identified for enhancing the sustainability of the production of agricultural products and for assuring food security. Concepts will be discussed in the larger framework of circular economy.

2. Legal framework

At EU level, production and use of animal feed are regulated in European Commission, 2002 (the General Food Law). Article 3 paragraph 4 defines animal feed as "*all substances and products, including additives, processed, partially processed or unprocessed, which are to be used for oral feeding to animals*". Further provisions are laid down in European Commission, 2009. Annex III of this Regulation provides a list of materials that are prohibited as animal feed (ingredient), including manure, construction and urban waste, glass, household waste, treated seeds, skins (leather) and wood, packaging material. Products or by-products that are suitable for, and in practice used as ingredients in animal feed, are listed in the EC Animal Feed Ingredient Catalogue (European Commission, 2013). Ingredients of compound feed are in a diverse range of cases actual residual materials with a long history of application, predominantly originating from the food production chain: oil production (expellers, pulp), flour and starch (chaff, bran, groats, hulls, middlings), legumes (hulls, flakes), forage (straw, silage), beer or more general ethanol production (distiller's grains, solubles), bakery products (dough, over-date products), residual streams containing animal by-products or consisting entirely of it (slaughter by-products, food products which partly consist of animal products), and a number of smaller streams. The intention of the Feed Catalogue is not to authorize the use of new ingredients or to prohibit the ones that are not included, but to facilitate that a listed ingredient complies to the definition as included in the Catalogue and should be labelled appropriately.

Waste is defined as materials for which the producer has the "intention to discard or is required to discard" (European Commission, 2008, Article 3, point 1). The legal indication of hazardous waste (European Commission, 2008, Annex III), which is an obliged part of lists of waste material, helps to exclude materials from feeding purposes. Feed is defined as materials for which the producer has the "intention to use for oral feeding of animals" (European Commission, 2002, Article 3, point 4). Between these two intentions at the top level of the hierarchy of materials, there are both other categories as well as grey zones. Non-food materials and appliances such as tools, hardware, industrial equipment, clothing etc. constitute another top-level category, of which the production results basically in all cases in a side stream of residual material. These materials are indicated as waste and are not intended nor feasible for animal feeding. Residual by-products from the food production chain have been evaluated as feed for insect rearing (European Food Safety Authority, 2015). An overview of restricted or prohibited materials as indicated by European Food Safety Authority, 2015 and listed in Annex III of European Commission, 2009 is presented in Table 1. The grey zone consists of, for example, materials indicated as waste in the general feed legislation (European Commission, 2009, Annex III) or in the Animal By-Product Regulation (European Commission, 2009) but excluded in the Waste Regulation (European Commission, 2008). For example, some materials, such as specific gardening or forest materials, are part of the definition of bio-waste in European Commission, 2008 (Article 3, point 4), are prohibited under specified circumstances (European Commission, 2009, Annex III), and are still included as feed material in the Feed Catalogue (European Commission, 2013, entry 7.14.1: untreated wood; <1% of wood fibres as aid in seed meals). In some evaluations and reviews residual materials historically used as feed ingredient have been included in the definition of food waste, which result in much higher volumes than would result from exclusion (Papargyropoulou et al., 2014; Makkar, 2017; Thieme and Makkar, 2017).

Further explanation on the use of food no longer intended for human consumption as feed material was published by the European Commission in April 2018 (Commission Notice, 2018/C 133/02). Two different groups are recognised in this notice: (a) all materials initially intended for human consumption and consisting exclusively of vegetal material, and (b) all materials initially intended for human consumption and consisting of, containing or being contaminated with animal proteins. Group (b) is subjected to the animal by-product regulations. Most notably, Regulation (EC) No 1069/2009 provide a set of three Categories for animal by-products, with specific application options for Category III materials. Group (a) consists of a whole range of different vegetal materials, including the classical by-products of food processing

Table 1
Categories of residual material with reference to legislative clauses. Group A – G taken from European Food Safety Authority, 2015. Italics: entry as mentioned in Regulation (EC) 767/2009, Annex III.

Substrate	Legislation
Group A: Animal feed materials according to the EU catalogue of feed materials (Regulation (EU) No 68/2013) and authorized as feed for food producing animals.	Regulation (EU) 68/2013 (Feed Catalogue) Regulation (EC) 767/2009, Article 4
Group B: Food produced for human consumption, but which is no longer intended for human consumption for reasons such as expired use-by date or due to problems of manufacturing or packaging defects. Meat and fish may be included in this category.	Regulation (EC) 767/2009, Annex I, point 1
Packaging from the use of products from the agri-food industry, and parts thereof.	Meat and/or fish containing: Regulation (EC) 999/2001, Annex IV, chapter II part c (aquafeed); Regulation (EU) 68/2013 (FC), item 9.14.1 Packaging: Regulation (EC) 767/2009, Annex III, paragraph 7
Group C: By-products from slaughterhouses (hides, hair, feathers, bones etc.) that do not enter the food chain originating from animals fit for human consumption.	In hydrolysed form, tricalciumphosphate: Regulation (EC) 999/2001, Annex IV, chapter II Regulation (EC) 1069/2009, art. 9 (Cat III), Article 11, point 11b Regulation (EU) 68/2013 (FC), items 9.10.1, 9.12.1
Hide treated with tanning substances, including its waste.	Regulation (EC) 767/2009, Annex III, Chapter 1, paragraph 2
Seeds and other plant-propagating materials which, after harvest, have undergone specific treatment with plant-protection products for their intended use (propagation), and any by-products derived therefrom.	Regulation (EC) 767/2009, Annex III, Chapter 1, paragraph 3 Chemical residues: Regulation (EC) 1831/2003
Group D: Food waste from food for human consumption of both animal and non-animal origin from restaurants, catering and household.	Catering: Regulation (EC) 1069/2009, Article 10-p (CAT III), art. 11-b; Regulation (EC) 142/2011, Annex I; Regulation (EU) 68/2013 (FC), item 9.9.1
Solid urban waste, such as household waste	Regulation (EC) 767/2009, Annex III, Chapter 1, paragraph 6 Household: Directive 2008/98/EC
Protein products obtained from yeasts of the Candida variety cultivated on n-alkanes.	Regulation (EC) 767/2009, Annex III, Chapter 1, paragraph 8
Group E: Animal manure and intestinal content.	Regulation (EC) 767/2009, Annex III, Chapter 1, paragraph 1
Faeces, urine and separated digestive tract content resulting from the emptying or removal of digestive tract, irrespective of any form of treatment or admixture.	Regulation (EC) 1069/2009, art. 9 (CAT II)
Group F: Other types of organic waste of vegetable nature such as gardening and forest material.	Regulation (EC) 68/2013 (FC), items 7.3.1, 7.8.1, 7.14.1
Wood, including sawdust or other materials derived from wood, which has been treated with wood preservatives as defined in Annex V to Directive 98/8/EC.	Regulation (EC) 767/2009, Annex III, Chapter 1, paragraph 4
Group G: Human manure, and sewage sludge.	Directive 2008/98/EC; Directive 91/271/EEC
All waste obtained from the various phases of the treatment of the urban, domestic and industrial waste water, as defined in Article 2 of Council Directive 91/271/EEC	Regulation (EC) 767/2009, Annex III, Chapter 1, paragraph 5

(including production of vegetable oil, flour and starch, ethanol), and final food products from retail. Retail is defined as '*the handling and/or processing of food and its storage at the point of sale or delivery to the final consumer, and includes distribution terminals, catering operations, factory canteens, institutional catering, restaurants and other similar food service operations, shops, supermarket distribution centres and wholesale outlets*' (European Commission, 2002, Article 3(7)). This is a logical description in itself: it covers all food sold to consumers, either for processing in their own household (shops, supermarkets) or for processing by professionals in restaurants, canteens, etc. and sold to consumers after processing. this. This definition covers both group (a) and group (b) as explained in Notice (2018)/C 133/02 of the Commission. Several side streams of retail currently restricted to shops and supermarkets, proven to consist only vegetal materials (group (a)) find their way to valorisation as feed ingredient such as bakery by-products (Kaltenegger et al., 2021). However, the definition of retail includes another partition. A difference is made between catering waste and household waste. Catering waste is defined as covering "*all waste food, including used cooking oil originating in restaurants, catering facilities and kitchens, including central kitchens and household kitchens*" (European Commission, 2011). The combination of the definition of catering waste and that of retail has the effect that a part of the catering waste material is included in "retail" (shops, supermarkets, restaurants, central kitchens), and that a remaining part is excluded from the definition of retail (household kitchens) because this is beyond the end-point of the food production chain. Besides the use of certain categories of spare material from shops and supermarkets with bakery by-products as example, the points of origin including factory canteens, institutional catering and restaurants at one side and household kitchens should be evaluated separately. Options for legal modifications to allow better valorisation are discussed in Meijer et al. (2023).

Certain legal provisions might be more relaxed or even absent in other legal systems than found in the strict EU legal framework. An important example can be the prohibition of re-feeding animal by-products to the same species. Even in the absence of a strict legal prohibition, the principle of anti-cannibalism can act as a measure to prevent zoonotic diseases and to avoid accumulation of undesirable substances in the feed and food production chain. Specific processing of animal by-products can be applied as alternatives in any circumstance, since the biological framework applies globally. Such technical solutions will be discussed in a next section of this paper.

3. Concepts of circular economy

Circular economy (CE) and its forerunners are concepts with a long history and a diverse interpretation (Cooper, 2011; Whitney, 2015; Reike et al., 2018). The report of the Club of Rome (Meadows et al., 1972) could be considered a turning point on the discussion of the role of mankind in using, depletion and spilling of natural resources. Reike et al. (2018) recognised three phases in the evolution of CE concepts. Up to the years 1990 the paradigm was to deal with waste in terms of reducing, reusing and recycling (CE 1.0). The emphasis was on the output side by principles such as "polluter pays". During the next evolutionary phase in the following two decades input and output of production processes were linked (CE 2.0). The aim was to achieve a win-win situation for both economy and environment (escaping the resource trap; see also Geissdoerfer et al., 2017). In this second phase, circularity was increasingly part of the strategies. Finally, the insight was developed that resource depletion should not limit economic growth. Therefore, during the years after approximately 2010, both new and revitalised older concepts are applied in the third phase of CE in order to achieve a decoupling of growth and environmental load (UNEP, 2011). At the same time, the "myth of decoupling" was put into discussion (Reike et al., 2018). In the course of the last decades, a large array of conceptual documentation was published on circular economy. Major reviews are published by Geng et al. (2012), Su et al. (2013), Papargyropoulou et al. (2014), Haas et al. (2015), Ghisellini et al. (2016), Korhonen et al. (2018) and Merli et al. (2018). The view that the concept of waste found its origin in the Industrial Revolution (White, 1967; Whitney, 2015) could be indicative for the situation that CE concepts primarily focus on non-food processes. The overviews of

Kirchherr et al. (2017) and Reike et al. (2018) mention only the existence of food waste without further discussion. Organisations focusing on food production and health such as FAO and WHO were not ranked among the non-governmental organisations including OECD, WEF and UNEP mentioned in these reviews (Reike et al., 2018). Current strategies focusing on food waste reduction (FAO, 2011, 2013; Borrello et al., 2017) would fit best in the concepts of CE 1.0. Muscat et al. (2021) mentioned five different factors for a circular bioeconomy. Some of these are part of general concepts ('avoid' would equal reduce, and 'prioritise' might be comparable to repurpose). Their 'safeguard' element, however, focuses on the principle that agricultural production processes should not exceed the capacity of the natural environment. This very relevant factor is not acknowledged as target in food production when the decoupling of growth from the environmental consequences, as advocated in CE 3.0, is aimed at.

The desire of achieving a circular economy is to limit the environmental load of human activities and to use or reuse by-products at the most valuable way. The proposition that waste does not exist in nature can be transformed to a principal concept for the production chain of feed and food. To a certain extent this concept has already been applied for vegetal materials by the historic application of side streams as ingredient in compound feeds. The ladder of Moerman (Waarts et al., 2011) provides an arrangement of destinations for valorisation of categories of food or bio waste. The retention options for non-food products (Reike et al., 2018), groups as used by European Food Safety Authority, 2015 for insect rearing and the categories of animal by-products (European Commission, 20099) can each be arranged along the sports of the ladder of Moerman (Table 2). The four classifications of materials are not designed with the same intention, and full congruity can therefore not be achieved. Nevertheless, the purpose of linking the four classifications is to illustrate that a process for gradually achieving a circular bioeconomy means that the different materials have to shift to higher sports along the ladder of Moerman, while maintaining the same or a highly comparable level of safety. The concepts of circular production systems and retention will be discussed further using the overview and terminology as discussed by Reike et al. (2018).

3.1. *Principal differences between food and non-food production chains*

The production chain of feed and food can only be compared to any other (industrial) production process to a certain extent. Retention options in CE for optimising production chains and closing loops are frequently presented as cascades or ladders (Reike et al., 2018). These options, up to ten in modern representations (Table 2), can be organised in three groups: client/user choices, product upgrade and downcycling. The client/user choices (refuse, reduce and resell) are comparable to the first three option in the ladder of Moerman (Table 2). At the lower end of the options, downcycling includes re-mine (landfill), recovery of energy, re-cycle and re-purpose ("re-wording" from Reike et al., 2018). In contrast, the middle segment of the retention options, product upgrade, shows large conceptual differences between biological and non-biological types of products. A majority of industrial products are assembled and can be disassembled as well up to a certain level, instead of being random mixtures. This disassembling is by principle necessary for the situation that the end-of-life state of industrial products is much more persistent than that of bio products. The latter will decay by natural processes, either catalysed for processing or spontaneous. Decay of by-products is a naturally existing process for down-grading materials, but at the same time this decay will shorten the shelf-life and increase microbiological hazards when stored for revaluation. This difference between biological and non-biological types of materials is only occasionally addressed (Ghisellini et al., 2016), and models for a circular bioeconomy exist which adopt the entire range of retention options regardless of their applicability (for example: Bos et al., 2021). The options repair (R3), refurbish (R4) and remanufacture (R5) are based on the principle of disassembling and reassembling of a few (R3), a set (R4) or most parts (R5) of the product. Composite food products, such as ready-made meals, sauces, soups or snacks cannot be disassembled to retrieve the original parts. Denatured starch or proteins will never return to their original three dimensional, tertiary or quaternary structure. The ladder of Moerman includes several alternative options. Specific chemical ingredients can be collected from a product, in some cases after chemical modification (biobased economy). This option can be

Table 2
Sports of the ladder of Moerman for valorisation of former food-products, compared to three other classifications: retention options for non-food residual materials (Reike et al., 2018), materials for insect rearing as mentioned by European Food Safety Authority, 2015, and categories of animal by-products in Regulation (EU) 1069/2009. Olive shading: actions as directed to human food, pink shading: destinations of animal by-products within the scope of Directive (2008)/98/EU article 2 part 2b (general waste directive).

Action or purpose (ladder of Moerman)	Retention options (Reike et al., 2018)	Materials mentioned by EFSA (2015)	Regulation (EU) 1069/2009
Prevention	R0: Refuse R1: Reduce		
Alternative use for human food	R2: Resell, Re-Use		
Conversion to human food			
Use in animal feed	"Regrade"	Unused food products not containing meat/fish (B)	Vegetal
		Organic waste from e.g. gardening, wood (part of F)	
		Intended by-products (A)	Cat 3, subjected to specific legislation
		Unused food products containing meat/fish (B)	
Industrial use (biobased economy)	"R8: Recover (components)"	By-products from slaughterhouse (C)	
		Food waste from human consumption (D)	Cat 2
Processing for fermentation	R6: Repurpose	Animal manure, intestinal content (E)	Cat 2
		Organic waste from e.g. gardening, wood (part of F)	
		Human manure, sewage sludge (G)	
Composting	R7: Recycle		Cat 2
Sustainable energy	R8: Recover (energy)		Cat 1
Burning (incineration)			
Land fill	R9: Remine		

compared to a special version of the option to recover (R8; Reike et al., 2018). Examples are discussed in the next section. New purposes of former food products can be implemented in two ways: use for fermentation (R6: repurpose), which can be seen as downgrading from the original food-grade level, and use as feed ingredient, which can be indicated as "regrading", a term not listed in the literature on circular economy (Reike et al., 2018). A major issue is the presence of a large array of types of plastic or other packaging material in former food products, which are in most cases carbon-based products as well. The mixture of organic matter of two kinds, feed and food of animal or plant origin together with packaging material (e.g. plastic) of industrial origin, the latter intended for conservation, induces a major issue for safe utilisation (Van Raamsdonk et al., 2011; Pinotti et al., 2021).

A lot of processes for feed and food preparation are biology driven. At one hand the consumption of farmed animals and transformation of materials to animal proteins is obviously a biological process. At the other side of the spectrum, processes such as fermentation and composting are also based on a biological conversion, e.g. by applying bacteria or moulds. Insects, used for conversion of low value to high value proteins, are being used in a range of countries globally, but gained interest in Europe only recently. Fig. 1 shows a general overview of relationships among major groups of living organisms. Besides the principle of biological distances among different species groups, the different preferences for diets –carnivory, herbivory, insectivory, mycophagy, coprophagy, etc.– would provide a further option of specific case-by-case scenarios for retention in the food production chain. It has been shown during the BSE crisis that herbivory animals (ruminants, rabbits) need to be respected. In other situations, such as omnivory (pig, poultry), coprivory (fecal material; some insects), xylophagy (wood; termites) or geophagy (inorganic material; earthworms), diets can contain a wider range of ingredients or diets can accommodate specific niches. Biological principles can add considerably to the concept of circular bioeconomy.

There are several undisputable principles for any design of the feed or food production systems. Safety of feed and food is an intrinsic part of these systems. A set of four basic safety domains can be distinguished. These include hazards in the area of biology, e.g. prions, viruses and unintentional presence of plant toxins and mycotoxins, in the area of chemical compounds without a direct biological source, e.g. pesticides, antibiotics, growth promotors, heavy metals and process contaminants (e.g. dioxins), in the area of microbiology such as bacteria, zoonoses and pathogens, and in the area of physics, e.g. microparticles and packaging material. These elements of what can be indicated as the BCMP cocktail are laid down in several EU directives and regulations (Directive 2002/32/EC, European Commission, 2003, European Commission, 2001, a.o.). Some of these domains are well addressed, whereas others are poorly understood. The latter holds in particular for the domain of physical hazards. A discipline studying physical harm, parallel to toxicology for chemical hazards, should fill the gap in the BCMP safety cocktail. First attempts for collecting data in the domain of physical hazards include papers on global exposure (Geyer et al., 2017), physicokinetics of nanoparticles in bivalves (Al-Sid-Cheikh et al., 2018), adverse effects of macroplastic in sea birds (Roman et al., 2019) and adverse effects of microplastics in aquatic environments (Ogonowski et al., 2016, 2018; Martínez-Gómez et al., 2017; Gerdes et al., 2018; Redondo-Hasselerharm et al., 2018).

Several factors specifically relevant for biological production systems will be presented and discussed in the following sections.

3.2. Relationship between species

In the view of the biological dimension of feed and food production, genetic distances between species, either consumers, producers or producer-consumer relationships, are being used in several ways. An

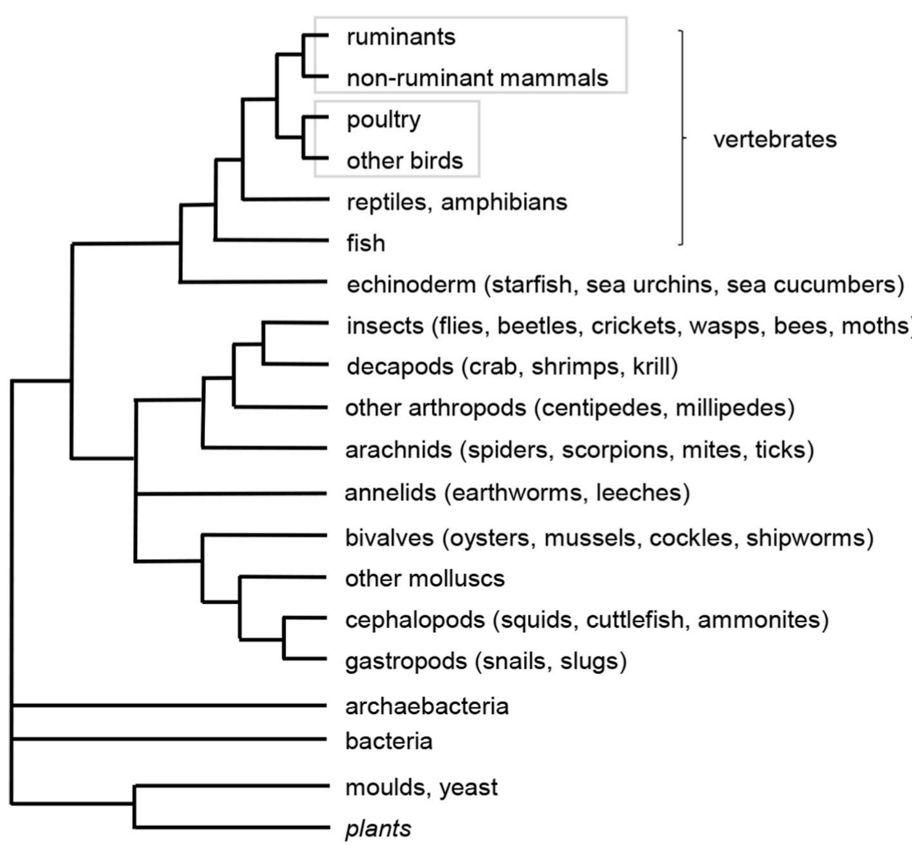

Fig. 1. General classification tree of living organisms intended to show relative genetic distances for support of feed and food safety issues. The subtrees in the grey lined boxes are presented in more detail in Van Raamsdonk et al., 2019).

example is the establishment of close relatives to human beings (e.g. 96% congruence between human and chimpanzee genomes) and the resulting choice of a representative model system for testing human susceptibility for diseases. For example, macaque apes were used as animal model for testing the infectivity of Chronic Wasting Disorder prions for their close relationship with humans (Race et al., 2018). A legally established way of applying the biological distance concept is the species-to-species ban which prevents cannibalism (disruption of a strict producer-consumer relationship; European Commission, 2009, article 11). This concept can be applied in a wider perspective. Animal by-products should be consumed by species with a relationship as wide as possible with the producing species in terms of biological relationship (Fig. 1). Consuming species can be assumed to be the least susceptible to pathogens, zoonoses and genetic diseases if the relationship with the source species is as low as possible. An example is the use of insects, which can be a valuable system for converting low valued materials such as former food products in high valued proteins (Pinotti et al., 2019). This principle can be extended to a variety of commodities matching their natural feeding systems. The physiology and genetic composition of insects provide a relatively low probability of active proliferation of pathogens and zoonotic diseases. Despite this, transfer of chemical contaminants and bacteria by insects has been demonstrated (Van der Fels-Klerx et al., 2018). This example will be discussed further in the section of technical options for conversion.

3.3. From closed loops to food webs

The major aim of transferring a linear economy to a circular economy is to make closed loops for minimising the ecologic footprint, and assuring economic profit. Elements recovered from old batteries can be used for the manufacturing of new batteries. Automotive parts or materials can be used for the production of new automobiles. Metal alloys or glass can be melted to produce new metal or glass products. In these and comparable situations recycling, recovering and reutilisation do not principally pose additional risks compared to the use of virgin materials. However, installing this type of closed short loops in the feed and food production chains could result in additional risks because of the possible short genetic distance between producing and consuming animals, or even lack of any distance. The use of ruminant slaughter by-products in the feeding of ruminants in the United Kingdom resulted in an epidemic of the mad cow disease (Prince et al., 2003). After several cases in Germany, Spain and Portugal in 2000, severe legislation was put in force in the European Union for preventing the use of animal by-products in feeding (see overview of legislation in Van Van Raamsdonk et al., 2019). Besides a strict ban on the use of ruminant by-products, the species-to-species ban was a logical consequence of this epidemic. A short loop will result in re-entering food waste in the same production system. In a general sense, such short loops or reuse of resources will have the potential hazard of accumulation. It is therefore recommended to apply principles of food webs and "route diversification" of materials in the production of feed and food (Fig. 2). By-products of one system are to be exchanged with other systems, either livestock husbandry or non-livestock processes such as fermentation. This principle of intertwined resource use has several advantages, such as a high flexibility and an intrinsic prevention of excessive accumulation of food safety hazards. By-products can be flexibly applied in those processes with the highest yield or demand. Prevention of accumulation of hazardous compounds should be supported by systems for physical monitoring of the presence in food production materials. Systems loss, e.g. wastewater, processing water, gasses, provide opportunities as well (Kasmi, 2018; Haddadi et al., 2018). Risk assessments should be mandatory in all cases of new application of materials. *In silico* modelling of processes can produce further insight in risks. Outbreaks of CSF in Spain have been successfully predicted and explained using a model with 22 parameters, although feed as a vector was excluded (Martínez-López et al., 2011; 2012). Life Cycle Assessments can be helpful to get insights in processes and relationships along the proposed production chain (van Van Zanten et al., 2016; Salomone et al., 2017; Salemdeeb et al., 2017; Sampaio et al., 2017).

3.4. Local loops

Local use of by-products can be an instrument for circular agriculture. After a period of economic growth and the correlated need to maintain or enhance profits by achieving international trade, a movement into the opposite direction occurred in the last decades. In the view of a decrease in urban farming in Europe and North America, and an increase in other regions of the world, a proposal for exchange of urban farming technology was published in 1980 (Smit, 1980). Since then, small scale farming or urban farming is a developing part of the entire sector of agricultural production. Initiatives are taken globally across all societies (Maxwell and Zziwa, 1992; horticulture in general: Grard et al., 2018; Nandwani, 2018; horticulture in New York: Campbell, 2016; livestock Nairobi: Alarcon et al., 2017; traditional food production

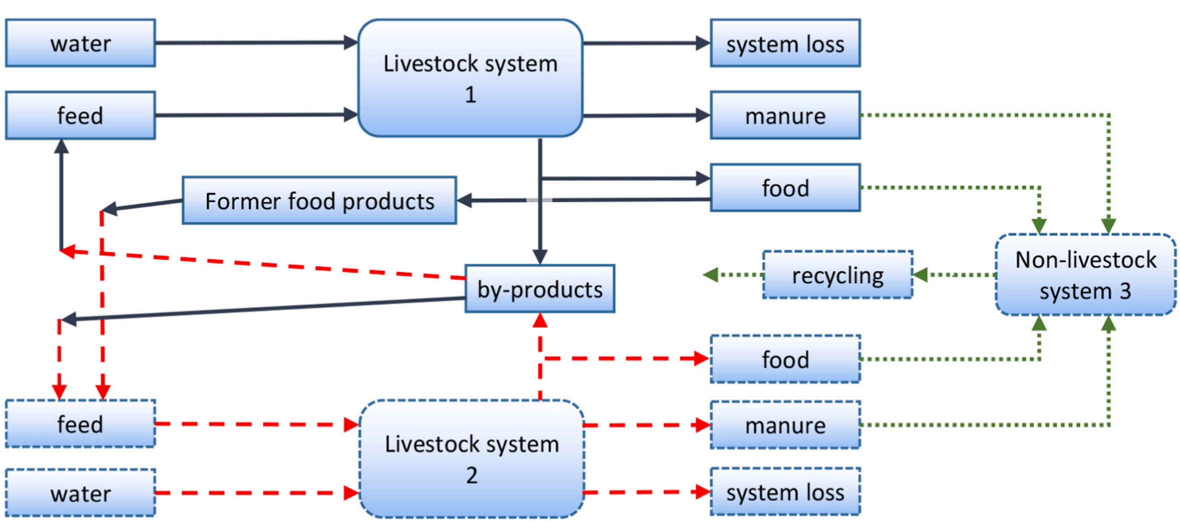

Fig. 2. Scheme of a livestock production system (1) with routes for recycling of food loss and animal by-products (blue straight arrows). Another livestock production system (2) can be used for creating a food web and preventing excessive accumulation of hazardous compounds (red dashed arrows). Other non-livestock systems (3), such as fermentation, can be connected as well (green pointed arrows). System loss is pointing to gasses and liquids which are leaked to the environment or collected for other, e.g. industrial, purposes.

Hawai: Kurashima et al., 2019). Small scale or urban farming activities are usually implemented in local societies, resulting in short transportation routes for resources and for delivery of their products. The resources would ideally include all kind of by-products resulting from food processing and consumption up to the use of manure, either animal or human (Wiskerke et al., 2018; Rehman et al., 2019). However, the legal set of limitations for the use of these by-products is primarily supportive of companies and counteract small-scale initiatives, due to both overhead costs and management structures for institutional procedures (Vermeij et al., 2017). Although the current legal framework for feed and food production is based on experiences with epidemics in the past and has the intention to produce feed and food as safe as possible, policy-making and legal requirements in general are recognised as prohibiting factors for several new developments (Gatrell et al., 2016; Campbell, 2016; Sutherland and Huttunen, 2018).

After presenting the specific concepts involved in circular bioeconomy, the development and discussion of technical solutions will be addressed. The following paragraphs will present some building blocks for strategies to achieve a re-evaluation of the opportunities to use certain bio materials.

4. Technical solutions for conversion

The current EU legislation has basically two sets of options for processing animal by-products when reusing as feed ingredient is prohibited. These are fermentation or composting by organisms with a position at the lower end of the biological classification (bacteria, moulds; Fig. 1), or non-biological chemical processing. In general terms of retention options, these can be indicated as repurposing or recycling (Table 2). This section will discuss a larger range of potential conversion possibilities, taking advantage of biological and biochemical processes.

4.1. Biological conversion

Insects are only distantly related to the classic vertebrate farmed animals (ruminants, pigs, poultry; Fig. 1). Nevertheless, the restrictions in feeding of insects are currently fixed according to the legal principles applying to these conventional livestock animals. It is, however, part of the nature of specific insects to extract nutrients and energy from sources which are currently prohibited or strongly restricted for conventional livestock animals as a feed material. Examples are wood for rearing termites, and manure for rearing fly larvae (Rehman et al., 2019). Rearing insects on these materials, and using the insect as food or feed, may be a key intermediate step to using certain 'waste' products that would otherwise not be suitable for regrading as feed.

The safe use of insects for food and feed is dependent on the safety of the substrate, the nature and source of the hazard, species, life stage in which the insect is harvested, and rearing and processing conditions (European Food Safety Authority, 2015; van der Van der Fels-Klerx et al., 2018; Meyer et al., 2021). The safety of the substrate plays a predominant role in the safety of industrially reared insect species; but these are not always directly correlated, and largely species-specific. For instance, black soldier fly larvae (BSFL, *Hermetia illucens* (L.) Diptera: Stratiomyidae) bio-accumulate the heavy metal cadmium; while yellow mealworm (YMW, *Tenebrio molitor* (L.) Coleoptera: Tenebrionidae) do so, to a lesser extent, for arsenic (van der Van der Fels-Klerx et al., 2016). BSFL that had been reared on a substrate of former foodstuffs contaminated with plastic and carton packaging materials also bio-accumulated cadmium, as well as mineral oils and dioxins a.o. – but concentrations of these contaminants in the larvae were all below the respective legal limit in the EU (van der Van der Fels-Klerx et al., 2020). On the other hand, several studies have shown the capacity of BSFL to metabolically convert – and possibly detoxify – aflatoxin B_1 (Bosch et al., 2017; Meijer et al., 2019) and other mycotoxins (Broekhoven et al., 2017; Camenzuli et al., 2018). If insects are reared on manure, it is important to monitor specific substances such as veterinary medicines in order to avoid bioaccumulation (Berendsen et al., 2015, 2018). Mammalian prions are not naturally expressed nor genetically replicated in insects, but some insects may be able to act as a mechanical vector in case of infected substrates (European Food Safety Authority, 2015; van Van Raamsdonk et al., 2017). Inactivation with a factor of 10^3 to 10^6 is reported to result from hypochlorous acid treatment (Hughson et al., 2016; Giles et al., 2017). More research is needed to assess the capacity of insect species that are industrially reared for food and feed purposes to transfer prions.

Some studies have suggested fasting insects prior to harvest, in order to allow the insects to release their intestine content (European Food Safety Authority, 2015), but recent studies showed no significant efficacy of this process on microbiological loads (Inácio et al., 2021; Wynants et al., 2017). In the cases of uptake and accumulation as listed, processing or specifically hydrolysation of insect proteins might be a solution (Nongonierma and FitzGerald, 2017; Soares de Castro et al., 2018).

The application of the species-to-species ban deserves a further comment. The term "species" has varying definitions in legislation. Ruminants and poultry are both groups of more or less related species. In frequently used classification systems pig refers to a subspecies, with wild boar as the other subspecies of the same species. By-products of salmon hatcheries are prohibited in salmon feed, but wild caught fish, being a mixture of several fish species and probably including some salmon, is allowed to be fed in salmon hatcheries (van Van Raamsdonk et al., 2019). The same might apply to insect species, but this is not yet crystallised. Better definition of "species" and application of the ban on cannibalism are needed. In that respect, it can be argued to apply the "species-to-species" ban to biological classification levels closer to the level of species instead of pooling entire classes (e.g. bone fish, insects). This would not affect the current application of that ban to the classical farmed animal (ruminants, pigs, poultry), but would allow a more flexible use of other animals. For example, by-products of rearing flies (Diptera) will remain prohibited for feeding to Diptera, but could be allowed for feeding other insects such as beetles (Coleoptera). See further discussion in Meijer et al. (2023).

4.2. Heat sterilisation

Processing of animal material is a general way to eliminate or minimise food and feed safety issues. The severity and extent of the processing procedures can vary, depending on the material, intention of the treatment and on the animal species (-group) intended for consumption. Sterilisation can aid to the safety of former food products (FFPs). European Commission, 2011, Annex IV provides a range of seven described procedures for sterilisation intended to deactivate prions. The most frequently applied procedure, which is obligatory for ruminant material include heating at 133 °C during 20 min (Annex IV, method 1).

Heat sterilisation is also applied for achieving sufficient microbial safety levels. A treatment at 65 °C for 20 min was reported to be sufficient for an appropriate microbial quality, and as side effect, for reduction of the moisture percentage in kitchen waste, dairy and fruits (García et al., 2005). Sterilisation at 60–110 °C for up to 60 min of kitchen waste appeared to be not fully sufficient for reaching full inactivation (Jin et al., 2012). In contrast, complete sterilisation of catering waste was reported after 120 °C for 40 min with respect to moulds and yeasts, *Staphylococcus aureus* and total coliforms (Jin et al., 2012). Complete inactivation of norovirus and related viruses was achieved after 8 s at 80 °C. Model simulation based on these results showed that treatment at temperatures below 70 °C cannot be considered reliable (Bartsch et al., 2019). These data suggest that temperature is a parameter of higher importance than the duration of the treatment. The European Union funded project REFRESH reported several levels of inactivation of a range of zoonoses (Luyckx et al., 2019). Inactivation rates ranged from 1 log reduction to full inactivation (Table 3) using two sterilisation regimes fitting in the methods as listed in European Commission, 2011, Annex IV.

Table 3
Estimated reductions of activation of some major viruses after two heat/temperature treatments. Compiled from Luyckx et al. (2019), supplemental material Tables 1 and 2.

Abbreviation	Virus	Animal	Estimated log reductions after heat treatment	
			70 °C/30 min	100 °C/ 30 min
HP-PRRS	Highly Pathogenic Porcine Reproductive and Respiratory Syndrome	Swine	1 log	99 log
HP-AI	Highly Pathogenic Avian Influenza	Avian	0.5–2.5 log	1275 log
ND	Newcastle Disease	Avian	2.6–4 log	436 log
FMD	Foot and Mouth Disease	Multiple	5 log	179 log
ASF	African Swine Fever	Swine	Inactivated	
HP-PED	Highly pathogenic Porcine Epidemic diarrhoea	Swine	Inactivated	
CSF	Classical Swine Fever	Swine	Inactivated	

4.3. Chemical modification

Catering waste and kitchen waste is currently tested as feedstock at pilot plant scale for producing medium chain fatty acids. The basic process was developed between 2005 and 2009 for producing caproic and caprylic acid (Steinbusch, 2010). The patent granted for the process of chain elongation (European Patent EP 2271764 B1) describes the process for enzymatic production of C_8–C_{18} fatty acids. Improvements for higher yield were achieved (Grootscholten et al., 2013). Although originally intended for use as biofuel, medium chain fatty acids proved to be valuable in piglet feeding and as antibiotic replacers (Hanczakowska et al., 2016; Hanczakowska, 2017). In this way a solution for valuable use of a by-product of the food production chain could provide simultaneously a solution for the desire to minimise the use of antibiotics.

4.4. Hydrolysation of proteins

Processes of hydrolysation of proteins are mentioned in legislation in two different ways. These procedures include alkaline or heat treatment (European Commission, 2011, Annex IV), and treatment with acid or enzymes (European Commission, 2013). In contrast to acid, alkaline or enzyme processes, the sole treatment with heat, as applied to feather meal, is primarily meant to cut the S-bonds in the tertiary structure of a protein in order to enhance digestibility, without shortening the chain length. Hydrolysed proteins (HPs) have a broader range of authorised application than processed animal proteins (European Commission, 2009, article 11: the species-to-species ban applies only to Processed Animal Proteins as defined in European Commission, 2011, Annex I, 5). Nutritional value, health effects and applicability for feed production of hydrolysed proteins have been documented extensively, most notably in aquaculture (Chalamaiah et al., 2012; Hosomi et al., 2012; Oterhals and Samuelsen, 2015). Gelatine is a hydrolysed protein product specifically produced from collagen after alkaline or acid treatment, combined with a facultative heat treatment. Legal requirements and restrictions in use differ from those applying to hydrolysed proteins, but still a wider use compared to processed animal proteins is allowed (Flaudrops et al., 2015; Sampaio et al., 2017).

Legally, HPs are defined with two parameters: source, either non-ruminant or from ruminant hides and skins versus ruminant (remaining parts), and chain length, which should be smaller than 10000 Da for ruminant sources. However, most typical HPs still contain fractions of peptides with a higher chain length. The share of the remaining fraction of peptides exceeding 10000 Da can therefore be used as parameter for identifying the extend of the applied process of hydrolysation. An additional parameter is the solubility of the material. A Hydrolysation Index has been compiled for classifying batches as hydrolysed proteins or as PAPs in general. An Index value of 60%, which translates to a fraction of over 79% with a chain length below 10000 Da and a solubility exceeding 70%. This approach is only suitable for hydrolysed proteins as pure materials (Van Raamsdonk et al., 2022).

4.5. Fermentation

A specific type of biological conversion is fermentation. A range of fermented products exist of e.g., rice (Feed Catalogue entry: 1.6.23), wheat (1.11.8; 1.11.12; 1.11.22), grains or cereals in general (1.12.3; 1.12.6 - 1.12.11), soya (2.18.15), sugar beet (4.1.7–4.1.9), potato (4.8.12, 4.8.13), milk (8.8.1) and finally the microorganisms itself (12.1.1–12.1.12, 12.2.1–12.2.7). Fermentation is not mentioned in the animal by-products regulations for the production and use of feed materials, as a range of other processing methods. Fermentation is mentioned as part of the process of biogas production (European Commission, 2011, Annex IV, Chapter IV, Section 2 (C), part 2 (e)).

An example of fermentation is the enhancement of the digestibility of straw, by-product of the production of cereals. The application of wheat, rye, maize and rice as staple foods for their high carbohydrate content results in an annual production of straw between 50 and 110 million tonnes in the EU (Kretschmer et al., 2012), or 1000 million tonnes globally (Hermosilla et al., 2017). Besides utilisation in the production of biofuel and in stable management, cereal straw has limited nutritional value as feed material. The dominant presence of carbohydrates such as hemicelluloses and lignin in straw prevents a sufficient digestibility. Fermentation with specific fungi increases the digestibility sufficiently for use as roughage in ruminant farming (Kuijk et al., 2016; Hermosilla et al., 2017; Zhou et al., 2017; Nayan et al., 2019).

4.6. Catering waste as a composite problem

The use of catering waste, kitchen waste and household waste is prohibited in the feed production chain as mentioned in several EU Regulations (Table 1). Most notably the risks on transfer of FMD and ASF were associated with the feeding of catering waste (“swill”) among other sources (Knight-Jones and Rushton, 2013; Halasa et al., 2016). An overview of microbial health hazards of swill as a feed-stock is provided by Dame-Korevaar et al. (2021). In principle, proper heat-processing of the material, use of licensed facilities, and other controls being in place should be sufficient to render the swill safe (Dou et al., 2018). Recent outbreaks or increased incidence of viral swine diseases were reported in regions with minimal or no regulation (e.g. China, India, Vietnam): raw swill feeding was identified as the prime cause, although other risk factors such as exposure to infected feral pigs may also play a role in some cases (Dame-Korevaar et al., 2021; Bowman et al., 2020). Smart monitoring and enforcement strategies are being explored (Bijlsma et al., 2013; Smith et al., 2014; Guinat et al., 2017; Postel et al., 2018). Simultaneously, certain food-grade materials are re-graded as feed ingredient in the EU Feed Catalogue, such as dried plant blossoms (European Commission, 2013, item 7.4.1), dried broccoli (item 7.5.1) and dried leaves (item 7.7.1). It might be helpful to specify precisely after which stage in the food production chain by-products have to be classified as waste (catering, restaurant, household or otherwise) and what the precise definitions of these by-products should be. In general, it could be imagined that after the transfer of a product from the professional production chain to third parties, most notably consumers, enforcement is very complicated or is virtually impossible. This would imply that different strategies are needed for different types of catering waste or biowaste from retail, which should be implemented in future legislation.

4.7. Future directions

In the framework of Feed Catalogue item 13.1.1 (bakery products), bread and bread-like products are processed and used as feed ingredient after testing for the remnants of packaging material. Fruit and vegetable materials are primarily used for fermentation (Van Raamsdonk et al., 2011). One of the opportunities of urban farming is to use food-grade products such as bakery, vegetables and fruits from local shops for livestock feeding in urban farms, under the assumption that these products will be discarded exclusively for economic reasons and avoiding safety issues. Restrictions can be applied by excluding food-grade products containing meat or fish, and by excluding ruminant animals as target. These opportunities in the framework of urban farming provide the advantage of raising this type of products to a higher levelled sport in the ladder of Moerman, with short transportation routes for increased sustainability. The maximization of the genetic distance is also assured: vegetal material in particular is the primary feed source of farmed animals. The requirements following the elements of the BCMP cocktail for feed safety should be assured by the requirement of using food-grade material. The specification of materials for urban farming leaves the diversification of biowaste from restaurants, catering and households unaltered. Full vegetal materials from professional facilities such as restaurant kitchens could be used as well for feeding purposes. Dedicated processing solutions such as the production of medium chain fatty acids by chain elongation would provide additional solutions. Animal by-products can be subjected to hydrolysation even in the case of mixtures of source animals, since the species-to-species does not apply. Catering waste from domestic use is the final type of material awaiting a solution for valorisation as feed ingredient.

Another development with possible future consequences is the increasing availability of novel foods (in the context of European Commission, 2015), which might result in new types of by-products. However, from a biological perspective, these novel foods will be based on known nutritional needs, which means that they will consist of proteins, fatty acids, carbohydrates, vitamins, minerals and other micronutrients, and recognisable units based on mixtures of these components such as viruses. It can be assumed, therefore, that the presented technological solutions will apply to these novel foods as well. Hazards can occasionally occur when a novel food ingredient shows high levels of one or more micronutrients, which are not modified by hydrolysation, fermentation, biological conversion or another type of processing. Examples are accumulation of some undesirable substances in specific insects (Van der Fels-Klerx et al., 2018; Van der Fels-Klerx et al., 2020) or the presence of arsenic in brown sea weeds (van den Burg et al., 2013).

5. Monitoring of suitability and safety

As stated, safety is a corner stone for the production of feed and food, reflected in a range of legal measures. The previous section provided technical opportunities for conversion of by-products of the food chain, including end products such as catering waste, for safe use as feed ingredient, which can be applied regardless of the specifications of a legal system. In strict jurisdictions, such applications can only be achieved after compliance to the relevant legislation. A flow chart is presented in Fig. 3 indicating the necessary steps in monitoring along the EU legal system. Certain by-products such as former food products are already inspected for a range of contaminants including heavy metals, classical pesticides and dioxins (European Commission, 2002) as well as for a range of other chemical compounds in order to be approved as food material. If applicable, an administrative check could be sufficient in these cases. In contrast, a range of other legal measures pertain to variable conditions. These relate to hygiene conditions and to mycotoxins, which can increase due to mould infections. In general, microbiological hazards will shorten shelf-life and analytical verification is unavoidable. Physical hazards can be connected to former food products, since unpacking is necessary for a range of products. Finally, for the first phase for monitoring, compliance of the label declaration is important for fraud prevention. It is, above that, also an important factor for feed safety. Proper label information could reveal the presence of specific ingredients, which might point to a possible existence of regulated contaminants, related to that ingredient.

If by-products, complying to feed standards and with sufficient microbiological conditions do not contain unauthorised animal proteins, use as feed ingredient is legalised. In those cases that the label information indicates the presence of animal by-products or appropriate tests turn out to be positive, additional tests for veterinary medicines or growth promotors should be applied. This is an example of the situation that label declaration can reveal the presence of a certain category of ingredients in the product, making tests for related contaminants necessary. It has to be noted that labels can often consists of misleading information and physical monitoring remains important where administrative control is preferred. Depending on the result, the species-to-species ban can restrict the range of application of the tested by-product, or might indicate downgrading to non-feed applications. The animal by-product regulations are more complicated than just testing for the included species (singular or plural). Tissue-specific restrictions (e.g. blood meal versus blood products) and origin (e.g. non-healthy animals, fallen stock, restaurant and kitchen waste) are important factors as well. Nevertheless, further legal relaxations are essential for achieving better options for circularity and sustainability in the feed and food production chains in the EU (Meijer et al., 2023).

6. Concluding remarks

The strategies outlined in this article would allow certain materials to be shifted towards higher levelled sports at the ladder of Moerman – after proper conversion (Table 2).

The WISE principle is intended as framework for the development of legislation by addressing several requirements (Van Van Raamsdonk et al., 2017; Van Raamsdonk et al., 2019): Witfull (reasonable legal principles), Indicative (clear limits between prohibition and authorization), Societal supportive (public health, environment, economy), and Enforceable (presence of suited monitoring methods). Comparable principles were discussed by Robert Maxwell, as part of the risk evaluation of BSE in the UK (see Randall, 2009). The issue of how to manage and improve the relationship between policy, politics and science was specifically named (see Randall, 2009: p. 78). The existence of a legal framework meeting the societal demands, or to be more precise, which facilitates new technological opportunities, with continuing assurance of feed and food safety, needs to be optimised (Thieme and Makkar, 2017). If safety assessments of new opportunities do not result in approval of a higher valued use, new assessments of the regraded products should be planned in the future, e.g. within five years, in order to keep pace with the rapidly evolving technological innovations. A 'safe-by-design' approach, in which awareness of food and feed safety is implemented throughout the development of new products, should be employed to curtail monitoring costs to check for compliance. The balance between 'environmental, economic and safety' aspects should be included in such assessments (Barros et al., 2020; Focker et al., 2022).

In general, information extracted from the biological fundament of our feed and food production chain, such as the position of animals and feed materials in biological classification, and information from food webs for designing loops for recycling, is vital for a sustainable feed and food production. Smart processing systems, targeted at either achieving sufficient safety of by-products or extracting and optimising specific parts (fatty acids, proteins), are necessary for a circular agriculture.

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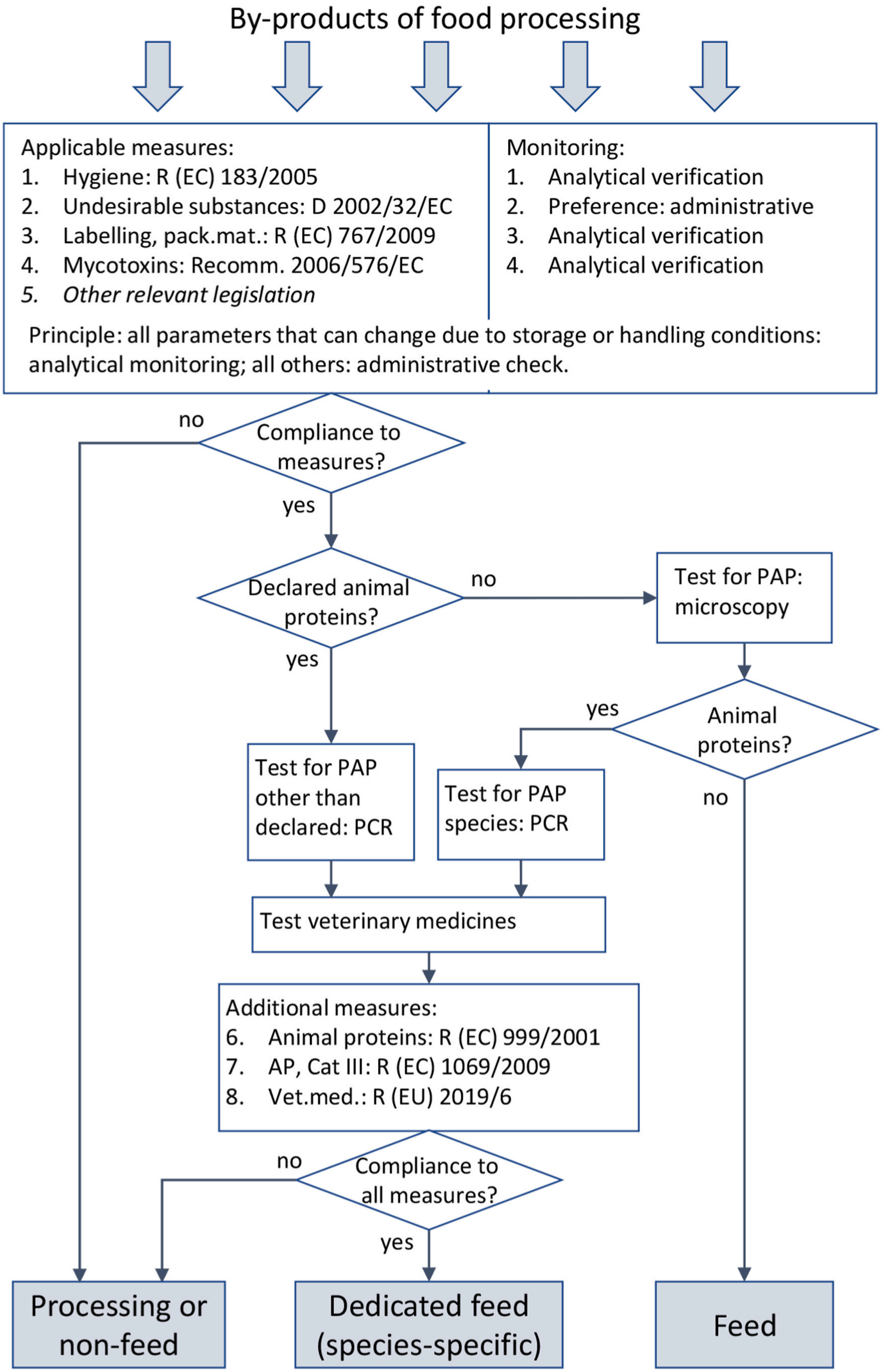

Fig. 3. Flow chart for monitoring former food products. Actions for monitoring are based on legal requirements. The results will point to regrading former food products as feed ingredient, either for general purpose or complying to the species-to-species ban, or downgrading to non-feed purposes.

Credit author statement

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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.

Data availability

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

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