**University of Veterinary Medicine, Budapest, Hungary**

# Emerging Food Chain Risks Related to Circular Economy

**Literature Review**

**Author: Ann Mariya, LQYYUA**

**Supervisor:**
**Dr. Zsuzsa Farkas**
**Dr. Ákos Józwiak**

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# List of Abbreviations

BBPs – Bakery By-products

FFPs – Former Food Products

FAO – Food and Agricultural Organization

HM – Heavy Metal

MeHg – Methyl Mercury

OCP – Organochlorine Compounds

PAE – Phthalate Esters

PAH – Polycyclic Aromatic Compounds

SCP – Single Cell Proteins

# Abstract

In recent years, there has been a rising interest in implementing sustainable practices to reduce dependence on finite resources and alleviate environmental burden has steered a gaining interest in the concept of the circular economy. This study is primarily dedicated to examining the emerging risks in implementing circular economy principles within the food chain, particularly emphasizing their application in animal feed systems. Notably, animal feed has gained considerable attention due to the competition for essential resources such as land and water required for both animal feed and human food production. Embracing circular food systems presents a promising solution to address climate change sustainably. However, as this transition is made, potential food safety hazards that might emerge must be addressed. The thesis depicts how circular economy principles and sustainable methodologies can be instrumental in animal feed production, focusing specifically on: the utilization of organic wastes and the novel feed sources. The microbiological, chemical, technological, and nutritional risks are collected and the findings of recent scientific publications are summarized. Given the elementary nature of this field, limited sources have been identified, signifying the requirement for further research to ascertain the practicality and efficacy of integrating these principles.

# 1. Introduction

The global food system stands as a major contributor to climate change, largely attributed to the inefficiencies inherent in the current linear systems; which involve unsustainable resource use and excessive food waste. Nonetheless, transitioning to a circular food system shows promise in addressing these challenges.

The Circular Economy Action Plan by the European Commission defines the concept of a "circular economy" as an approach that ensures the long-term preservation of product value, materials, and resources within the economy while minimizing waste generation (1). With global population growth and escalating resource demands expected to double in the future, there will be a surge in food and subsequently feed production. It is predicted that by the year 2050, there will be a 50% rise in the need for cereals, both for food and animal feed (2). Furthermore in developing nations, rising incomes are anticipated to drive significant growth in the demand for a range of food products, including meat, dairy, fish, aquaculture goods, and vegetable oils, surpassing the demand for cereals intended for human consumption (67).

The cost of animal feed is the largest expenditure in livestock production, accounting for 60 - 70% of annual expenses (3). At present, agriculture sector confronts a range of challenges, such as diminishing farmland, climate change, and the potential scarcity of water resources. Rising prices for conventional feed ingredients over the past decade have prompted researchers and producers in the animal feed sector to seek sustainable protein and energy sources for animal nutrition. Insects, former foodstuffs, food wastes, along with resources like duckweed and micro-algae, are considered promising alternative sources for protein and energy in animal feed. Presently, around 30% of the animal feed comprises by-products or leftovers from food production systems, according to the FAO (4).

During the implementation of these alternative feed sources, it is vital to consider and address potential emerging risks. An emerging risk is defined as “a risk that can emerge when there is a newly identified hazard, leading to the potential for significant exposure, or when there is an unexpected increase in exposure or susceptibility to a known hazard (5).” Assessing risk involves examining both the probability of a hazard occurring and the severity of its potential consequences.. Hazards, in this context, encompass potential sources of harm, including substances or conditions capable of inflicting health damage upon consumers.

Recognizing these emerging risks is vital for safeguarding the well-being of humans, animals, and plants within food systems. It also supports the development of strategic plans, comprehensive analysis, and effective risk assessment and management strategies to ensure the success of circular food systems.

The main objective of this thesis is to outline the identifiable risks associated with implementing a circular economy model for animal feed production. It focuses on two major areas: organic waste-derived feeds and novel feed sources. Organic waste-derived feed encompasses repurposed food products, food waste, and agricultural byproducts such as animal manure. Novel feed sources discussed include algae biomass and single-cell protein. The utilization of insects as feed represents a novel source, yet in this thesis, it is not discussed exclusively due to the existence of extensive studies and prior publications emphasizing their associated risks. As this is an emerging field of interest, there is still a substantial amount of work to be done in recognizing risks related to circular food systems. Therefore, this thesis aims to identify and highlight these risks.

# 2. Materials and Methods

The primary search platform used for this thesis was the Scopus search engine, from which relevant articles were selected from an assortment of peer reviewed articles and risks assessments. Initially, the key words specific to the question "what are the apparent risks for animals when circular economy or sustainable methods for feed productions are practiced?" were considered.

## 2.1. Key Word Selection:

| | |
|---|---|
| Stage | Key Word Selection |
| Date | 19/8/2023 – 24/8/2023 |
| Search Words | Circular economy, circular food systems, food safety hazards, food chain risk, food waste, food contamination, food production systems, food safety, feed safety, animal feed, feed production systems |

To identify suitable search terms for the query, a comprehensive search was carried out using a variety of keywords on different research platforms including Google Scholar and Scopus. Creating this keyword list played a crucial role in narrowing down the search terms and selecting the ones that appeared most frequently in articles.

## 2.2. Original Search Term:

| | |
|---|---|
| Stage | Non- specific search query |
| Date | 14/9/2023 – 21/9/2023 |
| Search Term | (TITLE-ABS-KEY ( "circular" W/3 "economy" ) AND TITLE-ABS-KEY ( "food*" OR "feed*" ) AND TITLE-ABS-KEY ( "hazard*" OR "risk*" ) ) |
| Relevance | Search results 365<br>1st selection: 166 (based on title)<br>2nd selection: 79 ( based on abstract)<br>Articles were then classified accordingly:<br>Animal feed alternatives/ substitutes : 18<br>Solid Waste/ Manure/ Municipal Sewage: 13<br>Phosphorus recycling: 4<br>Fertilizers/ Pesticides : 8<br>Articles based broadly on Circular economy : 19<br>Miscellaneous: 17 |

Out of this classification articles from animal feed alternatives and circular economy were selected, which consisted of 9 articles. Initially these words were considered helpful in in finding articles relevant to the query. But there was a gap in the search results and the articles found necessary, as there were not many articles addressing risks and hazards. As an initial draft, it has been acknowledged that not all the words were suitable for the study, and recognized the need for further refinement of this list.

## 2.3. Specific Search Terms

Due to the non-specificity of the previous search term. specific search terms were created to broaden search across various parts of the topic.

| Stage | Specific Search term |
|---|---|
| Date | 10/10/2023 – 18/10/2023 |
| Search Term | Risk and hazard specific:<br>( TITLE-ABS-KEY ( "risk*" OR "hazard*" ) AND TITLE-ABS-KEY ( "animal feed" ) AND TITLE-ABS-KEY ( "sustainability" ) )<br>Results: 79<br><br>Novel food sources specific:<br>( TITLE-ABS-KEY ( "novel" ) AND TITLE-ABS-KEY ( "food" OR "feed" ) AND TITLE-ABS-KEY ( "risks" OR "Hazards" ) AND TITLE-ABS-KEY ( "sustainable" OR "sustainability" OR "circular economy" ) )<br>Results: 561<br><br>Organic- derived waste specific:<br>( TITLE-ABS-KEY ( organic AND waste ) AND TITLE-ABS-KEY ( animal AND feed ) AND TITLE-ABS-KEY ( "risk" OR "Hazards" ) )<br>Results: 135 |
| Relevance | 22 articles |

## 2.4. Articles found from Bibliography of peer reviewed articles:

An additional 26 articles were collected from the reference lists of peer reviewed articles found on Scopus. These 4 articles (17), (20), (60), (61) served as the primary sources for obtaining information used in the compilation of the remaining articles within the thesis.

# 3. Results

## Emerging risks from circular food system

This literature review predominantly examines the risks associated with developing animal feed through repurposing organic waste and sustainable novel feed sources. While the focus is primarily on EU standards and limits, the review is also inclusive of other geographical regions. Within the framework of the European Green Deal, the European Commission has introduced a new Circular Economy Action Plan aimed at reducing reliance on natural resources and promoting sustainability (1). To advance this initiative, the EU has implemented diverse strategies, including the Farm to Fork strategy and a plan to halve food waste at the consumer and retail levels by 2030 (1).

The concept of circularity seeks to minimize waste production, ensuring that every by-product or waste substance is repurposed within some stage of food production. These materials undergo recycling and reuse within the food chain to maintain circularity (22). Food waste poses a significant environmental impact, contaminating air, land, and water, and contributing to the production of greenhouse gasses (22).

Organic waste from the food chain can be repurposed in various ways, depending on various factors. This review specifically addresses food leftovers, food waste, and agricultural waste, all of which undergo processing to reduce contaminant levels. Processing methods encompass thermal, chemical, and mechanical approaches (62). Novel feed sources are a new area of research interest. This review primarily focus on risks associated with using single cell proteins and algae biomass.

### 3.1 Repurposing Organic Products

Food waste refers to the loss of food at later stages of the food chain, often dependent on retail and consumer choices. Whereas food leftovers can be described as the foodstuffs that are no longer intended for human consumption due to manufacturing defects or any other practical reasons, and these reasons do not pose any health risks (6). European Commission regulations explicitly prohibit the use of certain materials in animal feed, encompassing waste products such as feces, as well as catering and household waste. Additionally, the practice of swill feeding is expressly prohibited (60).

### 3.1.1 Food Leftovers

Food leftovers can be broadly classified as former food products (FFPs) and bakery by-products (BBPs). Njezie et al. classified former food products as sugar rich products like biscuits, waffles and chocolate. Whereas bakery by-products contain food products such as bread, pasta, rice etc. (7). After collection from different sources of origin, they are unpacked and sorted after which they undergo processing; drying, grounding and sieving to acquire suitable feed ingredients which can be used as a substitute for ingredients that are used to formulate feedstuffs. Van Raamsdonk et al, demonstrated the use of candies and dairy powders to create syrups which can be used as a substitute for molasses or a binding agent to produce pelleted feed (8). In their study, Guo et al. used chocolate candy feed as a direct alternative to partially substitute lactose in nursery pigs, as it contains 50% simple sugars (9).

*Microbiological Risks:*

Microbiological risks are determined by a number of factors, but are mainly influenced by the processing of the feedstuff. The food leftovers undergo thermal processing during the feed conversion stage, this significantly lowers the moisture content of the food products hence contributing to the lower risk of microbial contamination (20).

*Technological Risks:*

The main risk pertaining here is the risk of contamination of the feedstuff with the packaging material. During the initial steps of processing the entire packaging are not manually removed, but it is first coarsely grinded together (13). The packaging remnants are then removed by wind sifting and sieving, metallic components are sorted out using magnets and eddy current (13). The most common packaging materials of food products are plastics, paper, cardboard and aluminium foil (10). The contamination levels of the packaging remnants were below the tolerance level set by European Commission (2011) (11)

*Nutritional risks:*

Monogastrics

Former food products (FFPs) and bakery by-products (BBPs) are utilized as cereal substitutes in pig feed in the specific case study conducted by Pinotti et al (11). An important characteristic to highlight is their high digestibility, this is influenced by starch gelatinization and protein denaturation which is a modification associated with the processing method (12). This enhances the large intestine's capacity to absorb higher amounts of readily absorbable nutrients, which is lower in animal feed containing raw materials. The high digestibility together with the higher rate of absorption of readily available simple sugars can affect the animals gut health by disrupting the microbiota (63). There can be detrimental effects when feeding post- weaned piglets highly digestible food leftovers as this can decrease the biodiversity and instability of the gut microbiota, leading to decrease in body weight gain, increasing risk of enteric pathogenic diseases and adversely affecting the immune system (63). Another nutrient deficiency is the availability of digestible amino acids; it is found that BBPs and FFPs have lower levels of amino acids and phosphorus, and reduced digestibility of all important amino acids when compared to corn meal (14).

Ruminants

A diet containing FFPs and/or BBPs is rich in energy due to the presence of high amounts of sugar, oil and starch. The abundance of these highly fermentable carbohydrates has a significant impact on the rumen fermentation and fibre degradation. Furthermore, the presence of high unsaturated fatty acids in BBPs contributes to a reduction in fibrinolytic bacteria, adding to the instability of the rumen environment (15).

In their research, Kaltenegger et al. found that incorporating 15-30% BBPs into the diet of mid-lactating cows increased the energy density. This was achieved by subsequently reducing the concentration of starch and neutral detergent fibre, consequently elevating the overall fat content. Consequently, this shift altered the cows' metabolism from a glycogenic pathway to a lipogenic one (16). Under these circumstances, cows fed BBPs experienced a lower risk of rumen acidosis compared to those on the control diet. This suggests that a diet containing 15% BBPs exhibited the lowest risk of developing rumen acidosis, followed by the 30% BBPs diet and then the control diet (70).

### 3.1.2 Food Waste

According to FAO, annually 1.3 billion tons of food waste is generated globally. This contributes to 8 -10% greenhouse gas emissions. Utilizing this food waste as a source of nutrients for animal feed can alleviate the burden imposed on the environment. Food waste is generated at the end stage of the human food chain (17).

Due to the current EU ban on using food waste as animal feed, 102,5 million tons of food waste generated within the EU are disposed (17).

Food waste is an excellent environment for growth of microorganism as it has high moisture and organic content. Rotting organic material can carry bacterial agents that can cause salmonella, toxoplasmosis etc., and using these substrates without proper treatment can lead to spread of pathogens. Therefore, microbiological risk has heightened relevance in food-waste derived animal feed (17).

*Nutritional Risks:*

Food waste broadly is constituted by 30 to 60% carbohydrates, 5 to 10% proteins and 10 to 40% fats (17). The studies conducted by Truong et al. with 56-day-old broilers showed that substituting 10% of their standard feed of corn/soy with dried bakery goods did not result in any significant variance in body weight or feed conversion ratio over the experimental period (56 days) (18). Similarly, Siddiqui et al., working with 42-day-old broilers, found that replacing 30% of the standard corn or soy feed with dried bakery waste did not lead to any significant changes in feed intake, feed conversion ratio, or body weight during the 42-day study (19).

*Microbiological Risks*

In the swine industry, feeding pigs constitutes about 80% of the overall expenses. Diseases like Classical Swine Fever (CSF), African Swine Fever (ASF), Porcine Respiratory and Reproductive Syndrome (PRRS), Foot and Mouth Disease (FMD), and Hepatitis E virus, which has the potential to transmit to swine through swill feeding, are of significant economic importance (20). Present regulations mandate the disposal of infected carcasses to prevent the re-entry of these waste products into the food chain due to the potential extreme risks involved. Consequently, legislation now strictly monitors waste disposal from slaughterhouses (20). Additionally, the outbreak of Bovine Spongiform Encephalopathy (BSE) prion in the UK was linked to feeding cattle BSE-infected bone meal additives (20).

*Chemical Risks*

Chen et al. analysed the chemical contamination levels in food waste resulting from human consumption, collected from different regions in China (21). The study results concluded that organic contaminants such as alfatoxin B1, DDT, hexochlorocyclohexane (HCH) and nitrites were all below the standard limit set by the Chinese Hygienic Standard for Feeds. Trace elements such as arsenic, cadmium and mercury were also below the standard limit. But in hydrothermally treated food wastes lead and chromium were found to exceed the standard limit (21).

Similarly, García et al. conducted an analysis in different categories of food wastes. They observed that lead content in restaurant and household wastes exceeded the EU limit values, metal packaging remnants like cans and pipes where suspected cause of contamination in this case (22). Cadmium was also found to be in high levels in household wastes but did not pose risk of toxicity as it did not exceed limit values.

Besides heavy metal and trace elements contamination, toxins present in certain food items can also pose risk to animal. In their study on utilising pumpkin waste as livestock feed, Laura et al. highlights the presence of toxin Cucurbitacins in the pumpkins. The concentration of this toxin varies in different parts of the plant and in different species; but mature parts have the highest concentration (23). In mice the lethal dose of this toxin is 5mg/kg, but the effects of this toxin highly variant in animals. Some animals such as coyotes, porcupines and wild boars show tolerance to this toxin (23). Băieş et al. found that supplementing pig fed with 500mg/kg *Cucurbita. pepo* had a pronounced anthelminthic effect (24).

### *Aquatic Feed*

In the aquaculture industry fish feed accounts for about 50% of the total expenses (25). Fish meal is the most predominantly used aqua feed, it serves has a good protein source as its contain essential amino acids, minerals and vitamins (26). Moreover, fish meal is one of the most expensive protein sources available. It is mainly used as aqua feed but pig and poultry industry uses approximately 40% of fish meal produced globally (27). One of the many downsides of using fish meal is the heavy metal contamination, this can lead to increase levels of heavy metal concentrations in farmed fish.

Cheng et al. studied the using of food waste as a substitute for fish meal. Food waste were collected from hotels and restaurants and processed into feed pellets for low trophic level fish such as bighead carp, mud carp and grass carp (28). These fishes show reduced susceptibility to accumulation of chemical contaminants (29).

*Phthalate esters (PAE)*

PAE is a widely used industrial additive in the production of plastics, it improves the flexibility, transparency and durability of plastic products. PAE contaminates food via contact in plastic containers, they can migrate into food particles during heating or in high fat foods, hence posing a risk of accumulation over time (30). Certain PAEs are shown to have detrimental effects on contamination, Dimethyl phthalate contamination in herring fishes can cause change in DNA conformation of these fishes (31). Whereas, Di-n-butyl phthalate is said to be lethal to zebrafish embryos (28). In rats Di-hexyl phthalate can cause abnormal reproductive tract development, sperm damage and disrupt endocrine hormone production (32).

In the collected food waste, fruits, vegetable, cereals and bone marrow had the highest concentrations of PAEs than other constituents. It is stipulated that this due to the increased exposure to fertilisers, pesticides and plastic film mulching (33).

Cheng et al. demonstrated that the concentrations of the PAEs in low trophic level fish were found to be at lower concentration levels than the fish fed control diets. It was noted that mud carp, which is a benthic level feeder had the highest level of PAEs amongst the three fish species (28). The health risk assessments of the fish tissue stated that there were no carcinogenic or non-carcinogenic risks for humans consuming these fish.

*Polycyclic aromatic compounds*

Polycyclic aromatic hydrocarbons (PAHs) is toxic contaminant which is a by-product of incomplete combustion of organic materials (34). They are an environmental concern as they persist in the environment for a long time in soil and aquatic sediments (35). They are very toxic having carcinogenic properties, bio accumulative ability leading to chronic toxicity (36) and can disrupt endocrine chemicals (37).

In their study Cheng et al., observed that commercial feed contained lower levels of PAHs in comparison to food waste feed. Even then, the fish fed with food waste diet had lower levels of PAH accumulation in tissues than the fish fed control diet. This finding could be partially justified as the fish fed in control diets were kept in experimental ponds in the Pearl River Delta, and the PAHs levels of the pond can be higher due to the contamination of water resources by industrial pollutants (38).

Moreover, the health risk assessment states that carcinogenic risk values were all below the suggested limit, therefore human consumption of these fish were considered safe (38).

*Organochlorine compounds*

Organochlorine compounds are a group of pesticides that are extremely toxic. Its use has been banned in many countries, despite this it is biomagnified through the food chain due to slow degradation and ability to bio accumulate. The results of the study by Cheng et al. indicates that fish fed with food waste diet (75% food waste) had lower level of OCP contamination than fish fed standard control diet (39).

This finding can be attributed to the fact that trash fish is an ingredient used in the production of fish meal, it can be a major reservoir of contaminants such as PCBs, DDT, PAH etc. Trash fish are species of fish that are considered inedible. Studies have revealed high levels of heavy metals such as cadmium (Cd) and lead (Pb) in fish meal derived from trash fish, contributing to the issue of metal contamination. Therefore, replacing food waste as protein source instead of fish meal can reduce levels of OCP in fish tissues (39).

### 3.1.3 Organic wastes

In order to achieve a sustainable food and feed production, the recovery and recycling of nutrients lost in waste and wastewater must be considered. This process can be very beneficial in utilizing valuable nutrients that would otherwise go to waste (66). However organic waste, despite their nutrient content, may harbor various organic and inorganic compounds that can contaminate biomass, making it unsuitable for feed or food production. Inorganic pollutants like heavy metals, pathogens, and various organic pollutants are potential contaminants that need careful consideration. There are various methods of bioconversion pursued to decrease the level of contamination as well as increase the nutritional value of the substance.

Fermentation emerges as a longstanding method to enhance the nutritional qualities of feeds or feed ingredients, converting abundant agricultural byproducts into viable alternative feed materials. Research confirms that feeding fermented feed is linked to improved feed digestibility and reduced ammonia emissions, contributing to environmental sustainability (65).

Insects have garnered attention for their role in bio-converting low-value substrates, like food byproducts and waste, into high-quality animal feed. Insects, due to their short life cycle, ability to grow on inexpensive feedstock (organic waste), limited land and water requirements, high conversion rate, low gas emissions, and overall sustainability, present advantages over traditional plants and livestock animals (64). Despite these methods appearing advantageous, this section addresses the risks associated with using feed obtained from the bioconversion of organic wastes.

*Insect converted feedstuff*

House fly, Black solider fly, blow fly and flesh fly maggots have been used for bioconversion of organic wastes to produce resourceful proteins. Depending on the substrate type the larvae can reduce the waste on varying proportions (67). Housefly larvae prefer animal manure, whereas blowfly and flesh fly larvae prefer meat substrates and black solider fly can thrive in variety of organic matter. These larvae effectively reduce the organic matter to produce fat which can be converted to biodiesel and protein rich insect meal. Although the amino acid content in the prepupal form is lower than that of fish meal, it remains a valuable resource (67).

*Chemical Risk*

The research conducted by Huang et al. focused on the use of housefly maggots (HM) to manage food waste and the resulting bioaccumulation of mercury (Hg). They found that feeding housefly maggots with food waste affected the Hg content, particularly in terms of methylmercury (MeHg) accumulation (68). The study revealed that different types of waste, such as vegetable and meat waste and rice waste, influenced the levels of Hg in the maggots. It was noted that the MeHg levels were significantly affected by the composition of the waste. Tilapia fed with food waste-grown housefly maggots showed lower mercury accumulation, although growth performance and nutrient content varied based on the type of maggots used. The research suggests that a specific mixture of vegetable, meat and rice waste in the maggot diet could effectively reduce the accumulation of MeHg. Overall, the study indicates that the housefly maggots exhibited low bioaccumulation of MeHg while transforming food waste, influencing Hg content and impacting the health and growth performance of tilapia (68).

*Fermented*

Mo et al., conducted a study analysing risk of heavy metal toxication from feed pellets created by fermenting food waste (69). The food waste used include cereals, meats, and vegetables, which were fermented for six days, processed at 80°C to create fish feed pellets. The study assessed concentrations of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury

(Hg), lead (Pb), and zinc (Zn) in the samples through plasma-mass spectrometry. The metal/loid concentrations detected in the fish feed pellets were below the limit values. The research conducted a health risk assessment to investigate the safety for consuming the fish this showed slightly higher hazard index values than control groups and market-purchased fish. However it was established consuming these fish posed no non- cancer risks to adults and children (69).

## 3.2 Novel Feed Sources:

As of our current understanding, the term 'novel feed' for animals lacks a specific definition in EU regulations. However, EU regulations clearly define novel foods for human consumption. According to Regulation (EU) 2015/2283, novel foods for humans are those not significantly consumed in the EU before May 15, 1997 (62). In the scope of animal feed, single-cell proteins and algal biomass emerge as highly promising alternatives. They serve as excellent sources of proteins and have the added advantage of requiring non-arable land for year-round cultivation. Exploring the potential for further development of these feedstuffs for mainstream feed production is therefore a valuable avenue for study (62).

### 3.2.1 Algal Biomass

Microalgae are important aquatic resources mainly consisting of autotrophic organisms. It is a good source for proteins, carbohydrates, lipids, micronutrients, vitamins, polyunsaturated fatty acids, and amino acids. They are presently used in several animal feeds, such as poultry feed additives, dog food etc. (40).

Markou et al. (2018) conducted an extensive study on micro algal growth utilizing waste and wastewater substrates. Their research showcased that nutrients can be efficiently recycled from these sources, subsequently reducing the freshwater demand for production. However, it also revealed that waste substrates bear substantial risks of microbiological and chemical contamination (40).

*Chemical risks*

Microalgae have been widely recognized for their potential in removing heavy metals (HMs) from aqueous solutions due to their significant affinities and high sorption capacities (40). The capability of these microorganisms for HM uptake is affected by various parameters, including the species of microalgae, the chemical species and concentrations of the HMs, co-existing ions, pH or salinity, and the nutrient status of the solution (41). A HM free biomass can be obtained by pre-treatment of the waste and wastewater systems. HMs are found in the solid fraction, with the degree of retention depending on the separation method and particle size of the solids. Microalgae thrive in the liquid portion of the digestate (42). Various studies have illustrated that the application of chelators, such as ethylenediaminetetraacetic acid (EDTA), has the potential to diminish or entirely eliminate the absorption of heavy metals (HMs) by microalgae (43).

*Microbiological risk*

The utilization of agro-industrial waste and wastewater for food and feed production using photosynthetic organisms is a complex challenge, primarily aiming to mitigate pathogen content and the potential transmission of pathogens to animals and humans (40). Bacterial pathogens like *Salmonella* and *E. coli* have the capacity to infiltrate plants through roots or shoots, establishing themselves within intercellular spaces and plant tissues (44). Pathogens adhering to surfaces might be more susceptible to removal or treatment compared to those located within cells. The presence of intracellular pathogens poses more significant challenges, alongside intercellular contamination issues (40). While some studies highlight a notable reduction in indicator bacteria such as *Staphylococcus aureus, Escherichia coli*, and *Enterococcus faecalis* during microalgae cultivation in wastewater, better understanding the cause of reduction of bacteria is necessary (45).

To address these pathogen concerns in waste biomass, various treatment methods are explored, including physical methods like UV exposure, pasteurization, and filtration, chemical processes such as alkaline treatment, chlorination, ozonation, and advanced oxidation, and biological methods like stabilization lagoons. However, the effectiveness of these methods can vary, with some failing to eliminate all pathogens and potentially producing toxic byproducts. Further research is essential to gain a deeper understanding of the microbiological risks associated with utilizing waste biomass as a substrate for algal and duckweed growth (46).

*Chemical Risks*

Hormonal growth promoters, including estrogens, testosterone, progesterone, and synthetic hormones used to boost animal growth and feed efficiency, are commonly integrated into livestock feed (47). However, when these compounds are excreted by the animals, they become environmental pollutants with endocrine-disrupting effects (47). During the cultivation of microalgae, estrogens undergo a transformation process, converting between different forms such as E1, E2, and EE2 within a few hours, followed by further breakdown into estriol and eventually into unknown lipophilic products after a more extended period (48). Although the final removal of total estrogen can exceed 85%, the medium's estrogenic activity might not decrease, suggesting that the degradation products demonstrate similar or even higher estrogenic activity than the parent compounds (48).

*Antibiotics*

The use of antibiotics in the livestock industry creates a risk of environmental contamination of the antibiotic residuals found in the animal manure (49). Microalgae have shown effective uptake mechanisms for antibiotics, contributing to the removal of over 88% of the compound in combination with photo-degradation, which accounts for about 21% of the elimination process. Particularly, the microalga *Phaeodactylum tricornutum* has displayed a notable sorption capacity for oxytetracycline, estimated at around 29 mg per gram of the algal biomass (50).

*Parasiticides*

The chemical compounds constituting different parasiticides pose a risk of toxicity in algae. At present, there is very little research on the uptake and metabolism of antiparasitic compounds (51). Weiner et al. (2004) discovered a link between how much atrazine, a compound, different microalgal species could take in and their sensitivity to it. The microalgae that were more sensitive to atrazine tended to gather more of it compared to the less sensitive ones. The researchers suggested that the species less sensitive to atrazine might either pump atrazine out of the cell or degrade it intracellularly (51).

### 3.2.2. Single cell proteins

Single cell proteins (SCPs) is an alternative protein source also known as bioprotein. It can be obtained from different microorganisms such as algae, fungi, bacteria and yeasts. Although its production requires a controlled environment there are very many benefits in producing protein source from microorganisms as they have a rapid rate of growth, require less space and have reduced water requirements (52). Articles reviewed utilized food biomass that would otherwise go to waste as growth substrates for SCPs microorganisms. Moreover, utilizing unused food for SCP production reduces expenses associated with storing, handling, processing, and disposing of surplus food, offering economic benefits and promoting sustainable practices (52).

*Nutritional Risks:*

Carbohydrates:

Protein derived from the single-cell protein (SCP), has been suggested as a valuable protein source suitable for both human and animal nutrition. Nevertheless Khan et al., found that the higher proportion of fermentable carbohydrates the yield of SCP increases, he demonstrated this by cultivating *S. cerevisiae* in potato peel based substrate having a carbohydrate content of 82% producing the highest yield amongst other vegetable substrates having lower carbohydrate content. For instance, wastewater derived from potato peels, when supplemented with glycerol, exhibited promise as a carbon source for SCP production. In another study, Kurcz et al. observed that Candida utilis can utilize potato peel wastewater as a substrate to yield 30g dw/L SCP and 12.2g/L protein. Pillaca-Pullo et al was able to utilize wastewater generated from processing coffee as a substrate to grow *Candida sorboxylosa*. It provided a nutrient rich matrix containing glucose, mannose and fructose which can be easily assimilated by yeast to produce 37 - 39% SCP (53). Date molasses is also a suitable substrate that supports the growth of yeast, as it provides a medium rich in reducing sugars (54).Orange peel not only provides a medium rich in carbohydrates but also calcium and potassium for the growth of *Candida utilis* to produce SCP (55).

Protein

The yield and composition of single-cell protein (SCP) are strongly influenced by the microorganisms used and the conditions of their cultivation. Various studies, such as those by Salazar-López et al., underscore the broad variability in protein content present in SCP derived from microalgae, ranging between 30% to 80% (56). This protein content in SCP generally surpasses that of conventional protein sources like soy, fish, meat, and milk . In a study done on Jian carp, the supplementation of *Methylocoocus capsulatus* in the fish feed showed significant improvement in the final weight, specific growth rate and serum antioxidant capacity, and a reduction in malondialdehyde (MDA) production when compared with fish fed on soybean meal feed (57). In a similar study done on farmed shrimp, an increase in growth was noted when 20% of the fishmeal was substituted by biofloc meal (58). High purine concentration in SCP could increase the uric acid concentration, posing risk to kidney stones. Hence, as a preventative careful selection of microorganisms must be made, which has low concentration of nucleic acids (59).

**Table 1:** Summary of the main findings of studies on risks associated with food production using Circular Economy principles.

| CE Context | | Nutritional Risks | Chemical Risks | Microbiological Risks | Other Risks | References |
|---|---|---|---|---|---|---|
| Repurposing organic wastes | Food Leftovers | Recognized/ Considerable | Not Recognized | Not Recognized | Technological risks: Recognized/ Not Considerable | (10), (11), (13), (15) |
| | Food Waste | Recognized/ Considerable | Recognized/ Considerable | Recognized/ Considerable | Not Recognized | (18), (19), (20), (21), (22). (23) |
| | | Aquatic Feed | | | | |
| | | Not Recognized | Recognized/ Not Considerable | Not Recognized | Not Recognized | (28), (38), (39) |
| | Organic Waste | Insect Converted | | | | |
| | | Not Recognized | Recognized/ Considerable | Not Recognized | Not Recognized | (67), (68) |
| | | Fermented | | | | |
| | | Not Recognized | Recognized/ Not Considerable | Not Recognized | Not Recognized | (69) |
| Novel Feed Sources | Algal Biomass | Not Recognized | Recognized/ Considerable | Recognized/ Considerable | Not Recognized | (41), (45), (48), (50), (51) |
| | Single Cell Protein | Recognized/ Not Considerable | Not Recognized | Not Recognized | Not Recognized | (52), (54), (55), (57), (58) |

## 4. Conclusion:

This literature review serves as an overview of the identified risks related to the utilization of sustainably sourced animal feed alternatives. Limited risks were identified primarily because this is a developing field that requires more comprehensive study.

Food leftovers are food no longer intended for human consumption, this makes a great alternative as animal feed. Although microbiological and technological risks were very low in the analyzed cases, there was a risk in terms of nutritional value (13). As they are very highly digestible due to increased amounts of readily digestible sugars, have low levels of phosphorus and amino acids this is likely to disturb gastro- intestinal microflora which might cause reduced body weight, immunosuppression and increase chances of enteric diseases (63). Ruminants may benefit from the energy-rich nature of BBPs, reducing the risk of rumen acidosis when appropriately integrated into their diets (15). The risks associated with nutritional value must be investigated across different types of food leftovers to conduct a comprehensive nutritional analysis. This analysis is crucial for determining whether these leftovers can effectively function as potential substitutes or additives in animal feed.

At present EU has banned using food waste as animal feed, especially meat waste for swill feeding (17). As part of nutritional risk analysis, broiler chickens were fed animal feed containing food waste, and their growth and performance showed no variation in comparison to standard feed (18), (19). Microbiological risk reports were very limited, but case reports suggesting disease transmission from swill feeding suggests the dangers of disease transmission via animal feed. Moreover, findings related to chemical risks indicated higher levels of lead and chromium in hydrothermally treated food wastes, emphasizing the need for cautious consideration and thorough examination of the safety implications associated with incorporating food waste into animal feed (22). This underscores the importance of continued research and comprehensive risk assessments to inform regulatory decisions regarding the utilization of food waste in animal nutrition.

Examining aquatic feed, the use of food waste as a substitute for fish meal involves evaluating potential contaminant risks such as phthalate esters, polycyclic aromatic compounds, and organochlorine compounds. Studies show that, despite lower concentrations in low trophic level fish fed with food waste, careful consideration must be given to potential health risks associated with these contaminants (28), (38), (39).

Sourcing organic agricultural waste as alternative feed sources, is yet another field of interest. Nutrients can be extracted from organic wastes through methods of bioconversion such as using insects and fermentation. Insect larvae can be utilized in degrading the organic waste into subsequent protein and biofuel sources (67). As part of risk analysis the mercury concentration in tilapia fish fed with insects produced through bioconversion showed no risks in mercury accumulation which impact the fish's health. This alone does not provide a comprehensive assessment of the safety of using this alternative, additional studies on other associated risks related to human consumption of these fish are necessary (68). As for fermented feed used as fish feed additives, it was found that heavy metal contamination was slightly higher than that of the control feed. Although this was deemed safe for consumption, a thorough analysis of other potential contaminants must be performed before the feed is sanctioned safe for consumption (69).

The exploration of novel feed sources, such as algal biomass and single-cell proteins, highlights the potential but also underscores the need for careful risk assessment (52). Algal biomass grown on waste and wastewater substrates may face challenges related to heavy metal absorption and microbiological risks (41). Single-cell proteins, while offering high protein content, require careful selection of microorganisms to avoid potential health risks, especially regarding purine concentration and its impact on kidney health. As we explore alternative feed sources, it becomes imperative to have a better understanding of these risks in order to maximize the full potential of these novel resources while ensuring sustainability and safety.

Recognizing these risks is crucial in effectively implementing circular economy principles in food production. Given the urgency of climate change and growing consumer demand for sustainable food sources, transitioning from current linear food production systems, which generate high amounts of waste and resource depletion, is necessary. Currently, not all potential facets are explored for risks in applying circular economic principles. More studies are required for a comprehensive risk analysis of alternative animal feed sources.

# 5. Summary

The objective of this thesis is to identify and address various risks associated with the adoption of Circular Economy principles in animal feed production. Circular economy is gaining prominence due to its focus on sustainability, centered around repurposing of resources to maintain circularity and reduce dependence on finite natural resources.

The literature review drew from research databases, revealing a limited number of articles, underscoring the emerging nature of this topic. Moreover, existing studies lack a dedicated focus on assessing whether risks align with the circular economy context.

The first section of the thesis explores repurposing organic waste, categorizing it into the use of food leftovers, food waste, and bio converted organic waste through insect conversion and fermentation as alternative feed sources. While the EU currently prohibits using food waste for animal feed, various regulatory authorities permit the utilization of food leftovers. Risks associated with nutrition are extensively discussed, microbiological and chemical risks are also mentioned, Special attention is given to the chemical contamination of aquatic feed, with findings indicating relatively low contamination levels in most feed alternatives.

The subsequent section introduces novel feed sources, specifically algal biomass and single-cell proteins (SCPs). Algal biomass is recognized as an excellent nutrient source, but concerns are raised regarding chemical contaminants, hormonal growth promoters, antibiotics, and parasiticides linked to the growth substrate used for algae cultivation. Single-cell proteins derived from microorganisms offer an alternative protein source, with nutritional risks encompassing considerations of carbohydrates, proteins, and potential purine concentrations.

In conclusion, the study underscores the need for further research to comprehensively address microbiological risks, chemical contaminants, and nutritional considerations in the context of Circular Economy principles applied to animal feed production.

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