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FOOD SAFETY

IN A CIRCULAR ECONOMY

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Laboratory analysis of foods and beverages in Thailand.

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Lemons in plastic bags for cold storage in Tajikistan.

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FOREWORD

Food safety, climate and nature are interconnected. The way food is grown and produced can contribute to climate change and biodiversity loss, which in turn weakens the agrifood system. A third of the food we produce is wasted, in part because of contamination, the risks of which grow as global temperatures rise.

The agrifood system is exhausted, but it also contains the solution to the world's most urgent challenges. To ensure food security and safety for everyone, we urgently need to transform the agrifood system to produce and use food more sustainably. This includes addressing food waste and other inefficiencies in the system, such as relying on limited natural resources and single-use materials.

To change the system, we need a new perspective. This means moving away from linear processes based on a "take-make-use-dispose" principle. Across the world, innovation is driving change across the agrifood sector – incorporating circular principles to improve the efficiency of resource chains and reduce waste. In contrast to a linear approach, a circular economy aims to manage materials sustainably within a closed-loop system, with more emphasis on sharing, reusing and recycling. Yet, the food safety implications of this transformation are not well understood and a critical knowledge gap remains. This publication by the Food and Agriculture Organization of the United Nations (FAO) provides knowledge on the important food safety considerations in a circular economy. Drawing on existing and emerging evidence, four key areas of interest are explored – water recycling and reuse, food loss and waste, food packaging waste, and integrated farming systems.

This report highlights specific food safety challenges and opportunities arising from circular production processes in different countries and contexts. Food safety concerns must not become a barrier to achieving circularity and its associated ecological, social and economic benefits. Instead, we must support knowledge production and build capacity to identify, characterize and mitigate food safety risks in circular processes. Important data gaps remain to improve the assessment and management of food safety risks, including microbiological risks and chemical contaminants.

Managing food safety risks is critical in order to prevent outbreaks of foodborne illnesses, achieve sustainability targets and ensure trust in the system. As the examples in this report demonstrate, public awareness and education are key, so that consumers who adopt more sustainable behaviours do not face increased food safety risks as a result.

This report contributes to FAO's Strategic Framework 2022–2031 and the transformation to more efficient, inclusive, resilient and sustainable agrifood systems for better production, better nutrition, a better environment, and a better life, leaving no one behind.

We need to work together to build a stronger, healthier agrifood system. Everyone – farmers, manufacturers, retailers, policymakers, researchers and consumers – has a role to play in harnessing innovation and addressing food safety as a priority in a circular transformation while providing safe food for everyone.

Corinna Hawkes

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An urban garden cooperative worker harvesting vegetables in the Bolivarian Republic of Venezuela.

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ABBREVIATIONS AND ACRONYMS

AMR	antimicrobial resistance
ARGs	antibiotic resistance genes
AUD	Australian dollar
BfR	Bundesinstitut für Risikobewertung
DEET	diethyltoluamide
DEHP	di-2-ethylhexyl phthalate
diPAPs	polyfluoroalkyl phosphate diesters
EC	European Commission
EFSA	European Food Safety Authority
EFSA CEF	European Food Safety Authority Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids
EFSA CONTAM	European Food Safety Authority Panel on Contaminants in the Food Chain
EFSA NDA	European Food Safety Authority Panel on Nutrition, Novel Foods and Food Allergens
FAO	Food and Agriculture Organization of the United Nations
FSANZ	Food Standards Australia New Zealand
FSIS	United States Department of Agriculture Food Safety and Inspection Service
GHG	greenhouse gas
HBCD	hexabromocyclododecane
HDPE	high-density polyethylene
IRDF	integrated rice–duck farming
JEMRA	Joint FAO/WHO Expert Meeting on Microbiological Risk Assessment
LDPE	low-density polyethylene
LMIC	low- and middle-income country
MGEs	mobile genetic elements
NIAS	non-intentionally added substances
OECD	Organisation for Economic Co-operation and Development
PAHs	polycyclic aromatic hydrocarbons

PBDEs	polybrominated diphenyl ethers
PCBs	polychlorinated biphenyls
PET	polyethylene terephthalate
PFAS	per- and polyfluorinated alkyl substances
PFBA	perfluorobutanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulphonic acid
qPCR	quantitative polymerase chain reaction
rRNA	ribosomal ribonucleic acid
SDG	Sustainable Development Goal
TCPP	tris(1-chloro-2-propyl) phosphate
UN	United Nations
UNEP	United Nations Environment Programme
USD	United States dollar
USDA	United States Department of Agriculture
US FDA	United States Food and Drug Administration
UV	ultraviolet
WHO	World Health Organization
WWC	World Water Council

cfu	colony forming unit
dw	dry weight
g	gram
kg	kilogram
l	litre
µm	micrometre
mg	milligram
ml	millilitre
mm	millimetre
org	organism

EXECUTIVE SUMMARY

Agrifood systems must produce sufficient, safe and nutritious food to ensure food security for all, while remaining within the planetary boundaries. Agrifood systems transformation is recognized as a key accelerator to achieving the Sustainable Development Goals (FAO, 2019a). One of the routes for this transformation is the introduction of circular processes and policies into agrifood systems. A circular agrifood system that retains waste as a resource coupled with designing out waste will change how food is produced, processed, sold and consumed. This represents a major departure from the predominantly linear processes – the "take-make-use-dispose" model – of the current system.

Circular production processes promise benefits towards sustainability across all dimensions – economic, environmental and social. However, these processes imply a departure from many assumptions upon which current food safety approaches are built. Leveraging the benefits of agrifood systems transformation will require adapting food safety policies and principles to ensure that food remains safe. Furthermore, new research will be needed to fill data gaps on the potential risks associated with circular systems.

Initiatives and innovations to build circular agrifood systems include treating and recycling alternative water sources, reusing and valorizing food waste and by-products, recycling and reusing food packaging, and building integrated farming systems to limit waste outputs. All these initiatives offer considerable promise in improving environmental sustainability and delivering potential gains for socioeconomic sustainability. However, there is growing evidence that contaminants, whether microbiological, chemical or physical, can be introduced and potentially accumulate during these circular processes. As the current understanding of such food safety risks is limited, this could lead to unsafe food and pose threats to commercialization.

While the food safety concerns raised in the context of circular agrifood systems are valid, they must not become barriers to realizing the opportunities for improving environmental sustainability. There is a growing body of guidance and resources on identifying, characterizing and mitigating food safety risks in circular processes. This developing knowledge base must be supported through targeted research, especially on emerging issues such as microplastics and antibiotic resistance genes in relation to the circular economy. As circular processes are increasingly adopted in society, it is essential to educate consumers to make safe and sustainable choices when purchasing, storing and disposing of food. Lastly, existing food safety regulations that could lead to food and packaging waste should be reviewed, exploring opportunities for flexibility without compromising on food safety.

Embedding food safety within transformed agrifood systems requires raising food safety outcomes to an equal level of importance as sustainability and economic performance. The characterization of food safety risks underpins the assurance that food is safe throughout the value chain. Researchers, farmers, product and food manufacturers, regulators and consumers all play a role in supporting the transformation to safe, circular agrifood systems. National and international food safety policies that are adaptable, outcome-based and flexible are essential in the transformation to circular systems. Aligning these policies will bring food safety further into the dimension of circular food processing and drive food waste reduction in international trade.

The purpose of this report is to consider the current and emerging evidence related to food safety risks in various circular production initiatives within agrifood systems. To emphasize the importance of food safety and identify opportunities to adopt circular agrifood processes and polices, this report covers the following topics:

> water recycling and reuse in agrifood systems;

> managing food waste and food production and processing by-products;

> managing food packaging waste;

> integrated agricultural systems to improve land use efficiency;

> policy considerations for circular agrifood systems, consumer adoption of circular practices, data gaps and ways forward.

BOX 1

WHAT IS CIRCULARITY?

While various definitions of circular economy have been proposed, varying by sector and the interconnectedness with environmental and health goals, the concept itself rests on the core principles of:

> Eliminating waste and pollution – by designing out waste and inefficiency in production chains.

> Circulating products and materials – by considering consumables and components of bio-based and technological production chains to achieve high efficiency in production.

> Regenerating nature – by introducing sustainable production practices and managing the exploitation of natural resources to maintain and improve natural capital.

Source: **Ellen MacArthur Foundation**. 2015. *Towards the Circular Economy. Economic and Business Rationale for an Accelerated Transition.* Cowes, UK, Ellen MacArthur Foundation.

CHAPTER 1

FOOD SAFETY IS KEY IN TRANSFORMING AGRIFOOD SYSTEMS TOWARDS CIRCULARITY

1.1 IMPORTANCE OF FOOD SAFETY IN ENSURING FOOD SECURITY

Foodborne diseases are a significant global contributor to morbidity and mortality. According to the World Health Organization (WHO), one in ten people globally suffer a foodborne illness every year, 40 percent of whom are children under five (WHO, 2015). Consequently, managing food safety is essential to protect public health, support longer life expectancy and improve quality of life. In addition, the economic impact of foodborne diseases is considerable, with recent estimates from Australia reporting an annual cost of AUD 2.44 billion, or AUD 9.3 million per 100 000 inhabitants, from foodborne pathogen-caused illnesses and sequalae (Australian National University, 2022). Across all low- and middle-income countries (LMICs), lost productivity from premature death and disability resulting from foodborne illnesses and their treatment has a total economic cost of approximately USD 110 billion a year[1] (Jaffee *et al.*, 2019). Ensuring food safety requires the participation of all actors across different stages of the food chain, with producers, manufacturers, consumers, distributors and policymakers working in tandem.

Food safety is an integral factor across the six dimensions of food security: availability; economic, social and physical access; utilization; stability; agency; and sustainability (High Level Panel of Experts on Food Security and Nutrition, 2020). Assuring food safety, aside from its direct role in consumer protection, facilitates international trade and underpins economic growth in agrifood systems worldwide (FAO and WHO, 2016).

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[1] Based on the estimates of gross national income per capita for 2016 and disability-adjusted life year (DALY) by subregion/country for 2010.

1.2 NEED FOR RESILIENCE FOR FUTURE FOOD SAFETY AND SECURITY

Food security and food safety are under unprecedented pressure from the challenges of climate change and resource depletion (FAO, 2020), while a global population estimated to reach 9.7 billion by 2050 requires sustained growth in the production of food that is both safe and nutritious (UN, 2019). Urbanization, changes in social infrastructure and increased purchasing power have changed consumer dietary preferences. For example, in China, the focus has shifted to convenience, demand for a high diversity of food products, and availability of non-staple commodities. This comes at a cost of increased resource demands and a greater environmental footprint from food production (Xiong *et al.*, 2020). Urban consumer awareness of the sustainability of dietary patterns is increasing but is often resistant to change (López Cifuentes *et al.*, 2023).

Building resilience into agrifood systems, raising awareness of global challenges and implementing equitable technological advancements are needed to help address challenges around agrifood systems transformation. However, these measures must be supported by waste reduction and more efficient use of natural resources.

1.3 SUSTAINABILITY CHALLENGES IN AGRIFOOD SYSTEMS

Historically, industrialization and technological advancements have allowed linear approaches ("take-make-use-dispose") to drive the economic model of the agrifood system. This model entails high levels of resource use, generation of waste and pollution. This is evident in multiple ways:

- Resources, including minerals, fresh water, arable land and fossil fuels, are limited and constantly require the exploitation of virgin sources (Holden *et al.*, 2018).
- The farm to fork system (cultivation, processing, manufacture, transport, storage and consumer use) is inherently inefficient, generating large amounts of edible and inedible food waste (FAO, 2019b; UNEP, 2021).
- Materials designed for single or limited use and with little potential for recovery are used throughout the agrifood system – in cultivation, food collection, packaging, laboratory testing and consumption (FAO, 2021).
- Wastes are often disposed of in landfills with no possibility of recovering them, producing greenhouse gas (GHG) emissions and generating other environmental impacts (FAO, 2019b).

There is growing consensus that this model is undesirable and unsustainable (FAO, 2019b). Furthermore, the impacts of generating and discarding waste have implications for planetary health, including the production of GHG emissions, as well as the ecological and human health impacts of wastes and contaminants leaking and leaching into the environment, requiring further resources to manage and remediate long-term waste repositories.

Four focused areas of interest for the agrifood system – water scarcity, food loss and waste, food packaging waste, and land use efficiency – are addressed in this report.

Certainly, other sustainability challenges exist in the agrifood system, such as a reliance on chemical inputs derived from fossil fuel extraction or on veterinary antibiotics for disease prevention and management, among others. However, these four areas were selected to highlight food safety considerations in the adoption of circular production processes and technologies. The problem statements for these four areas of interest are summarized in the following paragraphs.

1.3.1 WATER SCARCITY

Between 2000 and 2020, terrestrial water storage dropped 1 cm per year, while the frequency and length of droughts rose 29 percent globally (WMO, 2021). In the period 2015–2017, the Western Cape of South Africa suffered its worst drought since 1904 (Otto *et al.*, 2018), while in the United States of America, the Colorado River Basin has been experiencing a drought since 2000 (Gangopadhyay *et al.*, 2022). In 2023, countries in the Horn of Africa suffered the worst drought in the last 40 years, leading to high food insecurity (WHO, 2023).

Amid dwindling water resources across the world, the agricultural sector consumes over 70 percent of the water collected or abstracted from water sources in many regions (FAO and WWC, 2015). Furthermore, population growth and densification in urban areas is driving competition for water resources, requiring increased provision of fresh water for direct consumption. In northeastern Spain, for example, drought conditions led to legislating a 40 percent reduction in agricultural water usage (Jones, 2023). Managing water use effectively is a critical challenge for many countries and will continue to be a pressing issue in the coming decades.

1.3.2 FOOD LOSS AND WASTE

Food loss is the decrease in the quantity or quality of food occurring in the agrifood system in all production stages before retail (FAO, 2019b). It was estimated that 13.8 percent of the food produced throughout the world in 2016 was lost between harvest and retail markets, with part of this loss attributed to food contamination (FAO, 2019b). Food waste is the decrease in the quantity or quality of food at retail, food service and consumer levels (FAO, 2019b). Estimates suggest that 17 percent of food produced globally in 2019 was wasted at household, food service and retail levels, equating to 121 kg of wasted food per person per year (UNEP, 2021). Furthermore, large amounts of typically inedible by-products and residuals of food production and processing (here termed “food by-products”), such as rind, peels, shells and bones, are discarded. In a study conducted in the United States of America, it was estimated that 10 to 18 percent of the total expenditure on food consumed in the home and away from home is spent on inedible components that are discarded (Conrad, 2020). The food safety implications of valorizing food waste and food byproducts are discussed in this report.

Going forward, climate change impacts will exacerbate food waste. For example, increased climate variability and rising temperatures will affect storage temperatures and increase the geographic range of pest and disease vectors, such as mycotoxin-producing fungi, affecting more production areas (FAO, 2020). These conditions will exacerbate waste as food in production, storage or retail suffers qualitative loss and waste from toxin accumulation or the persistence of pathogens and from weather, pest damage and spoilage.

This high level of waste is a concern as food waste has a high GHG footprint, accounting for 8 to 10 percent of global GHG emissions (Mbow *et al.*, 2019). Food loss and waste also contribute to food insecurity by reducing the availability and increasing the price of food (FAO, 2019b).

1.3.3 FOOD PACKAGING WASTE

Non-biodegradable plastics make up a considerable portion of food packaging. An estimated 37.3 Mt of plastics were used in food packaging globally in 2018 (FAO, 2021b). Due to mismanagement, much of this plastic waste ends up in the environment, with most of it entering the world's oceans (The Pew Charitable Trusts and SYSTEMIQ, 2020). Producing plastic from fossil fuels contributes to GHG emissions while plastic waste also leads to air pollution and human exposure to hazardous chemicals when inappropriately disposed of (UNEP, 2023). Consequently, plastic waste has significant negative impacts on both human and environmental health (UNEP, 2014).

Conversely, however, packaging adds value in the agrifood system by reducing food waste (Licciardello, 2017; Guillard *et al.*, 2018). For example, in retail, food waste can be reduced through robust packaging that maintains food integrity, extending

Peeled oranges sold at a market in Senegal.

©Jane Hahn

the shelf life of foods and reducing loss from spoilage (Marsh and Bugusu, 2007). Thus, packaging plays a key role in sustaining and even increasing food security, yet the high waste burden of current packaging materials necessitates innovation to improve sustainability (Guillard *et al.*, 2018).

1.3.4 LAND USE EFFICIENCY

The challenge of producing sufficient food to maintain food security amid limited productive agricultural land requires more efficient land use. Intensive agricultural production systems can be highly efficient but demanding of nutrient inputs and agricultural chemicals to maintain fertility and manage pests and disease, which are costly to smallholder farmers (Chai *et al.*, 2021; Shyam *et al.*, 2023). Intensive agricultural production can have a large environmental footprint through loss of nutrients and waste, as well as direct and indirect GHG emissions. For example, intensive animal rearing or aquaculture produces high volumes of animal waste which, through excess nutrient loading and the excretion of veterinary medicines, can lead to adverse environmental impacts (Ahmad *et al.*, 2022).

Increasing land use efficiency for food production in a sustainable way requires optimizing on-farm resource use. An area of interest to achieve better land use efficiency is through diversifying production and integration within the farming system to better synergize nutrient cycles and resource sharing between species.

1.4 RE-ALIGNING THE AGRIFOOD SYSTEM TO CIRCULARITY

Considering the challenges in the coming years to maintain and enhance food security, there is a growing call for change in agrifood systems to produce and use food more sustainably. Achieving the 2030 Agenda for Sustainable Development requires systemic transformation, and the circular economy can contribute to multiple Sustainable Development Goals (SDGs). Economic, social and environmental factors are driving agrifood systems change. These include:

- resource scarcity and the depletion of natural resources such as water and soil;
- a growing global population and increasing food demand;
- the need to reduce emissions and mitigate climate change;
- the rising costs of inputs and waste disposal;
- the need to increase resilience and adaptation to environmental shocks and disruptions in the food system; and
- consumer demand for sustainable and ethical food production practices.

Decoupling economic growth from mainly virgin resource use is a focus of SDG 12: Ensure sustainable consumption and production patterns (UN, 2015). This goal establishes targets for achieving the sustainable management and efficient use of resources. Further targets address food waste, reducing waste generation, increasing awareness of sustainable development and lifestyles, and achieving the environmentally sound management of chemicals and waste throughout their life cycle. Achieving SDG 12 requires sustained, holistic efforts to make our agrifood systems more productive and less wasteful.

To achieve sustainability in agrifood systems, better retain value overall and reduce waste, it is essential to move away from a linear approach (Osorio, Flórez-López and Grande-Tovar, 2021). Circular food production and use will address many of the issues previously described. In practice, the adoption of circular production principles into agrifood systems means:

> improving the efficiency of resource chains so that waste is limited, including, for instance, improving production processes to limit or valorize by-products, overproduction and defective products;
> changing planning and design, so that consumables last longer and can be recovered at end of life, for instance through the substitution of materials, removing single-use products, and product stewardship programs to return end-of-life product to manufacturers, where applicable; and
> improving waste streams to recover and reuse waste materials for processing chains.

Advancing circular practices requires a better understanding of how to act to transform the current linear system. For instance, a review by the European Food Safety Authority (EFSA) identified four macro areas of action including: those related to the primary production of food and feed such as the use of organic waste streams for farming insects; reducing industrial, manufacturing and processing waste; reducing food and feed waste in wholesale, food retail, catering and households; and reducing food and feed packaging waste (EFSA, 2022). Across these four areas, 25 circular practices were identified in the literature review ranging from technical practices, such as *in vitro* production of meat, to policy actions, such as curtailing antibiotic use to reduce antibiotic resistance genes (ARGs) in livestock waste, and educational efforts, such as staff training to reduce food waste.

To ensure long-term food security and improve resource use efficiency and environmental performance, the current agrifood system model must be realigned. A systems approach to improving sustainability in agrifood systems aims to advance circular processes and policies designed to reduce waste by closing material and processing loops. For this transformation to take place, agrifood system production processes must be redesigned to align with circular economy principles. This means that products must be redesigned to limit waste and enable upgrading and refurbishment to prolong their use, and that value is derived in the reclamation and reuse of resources from waste. Further measures are needed to increase the efficiency of resource use and consumption and reduce wastage in processing chains.

1.5 THE ROLE OF FOOD SAFETY IN TRANSFORMING TO CIRCULARITY

To improve the environmental sustainability of agrifood systems, it is critical to evaluate current agrifood systems, holistically plan and implement the transformation to circularity and address food safety. For example, adopting reusable food packaging will reduce the demand for raw resources and landfill capacity. However, it is necessary to ensure protection from contamination comparable to that achieved with the use of single-use packaging. Otherwise, food waste will increase and there may be an increased incidence of foodborne diseases (Matthews, Moran and Jaiswal, 2021). When planning to adopt reusable packaging, the volume of water and disinfectants needed to clean containers properly for reuse must be assessed (Landi, Germani and Marconi, 2019). Circularity in agrifood systems requires food safety assessments based on various risk profiles, as is the case of fertilizer production (Box 2).

Circularity in agrifood systems differs from other resource chains as it involves effectively managing perishable products with defined shelf lives to prevent spoilage and utilize the waste continually being generated. Food safety hazards typically enter an agrifood system at various stages. Once introduced within a closed-loop system, there is a potential for food safety hazards to persist and accumulate (Thakali and MacRae, 2021). Therefore, the adoption of circular agrifood practices and policies requires a proper analysis of vulnerable entry points and risks, so that comprehensive food safety measures can be implemented within circular production processes. Limited understanding and assumptions regarding food safety management, typically shaped by the features of linear production systems, pose a challenge to circular transformation.

At present, the key outputs being evaluated in the adoption of circular practices are their economic, environmental and social performance (Rico Lugo, Kimita and Nishino, 2023). However, there is limited knowledge of the food safety risks that might be introduced or exacerbated by circular agrifood processes and polices, in particular the critical points at which these risks might emerge (Focker *et al.*, 2022).

In addition, many of the practices in contemporary food safety, including monitoring and assurance, derive from linear "take-make-use-dispose" processes:

> Contaminated and adulterated food products tend to be considered as waste (FSIS, 2006).

> Virgin resources are preferred over recycled materials due to the reduced risk of contamination from prior use.

> Single-use materials are used in food production and testing to maintain hygienic conditions.

Assessing and managing food safety risk is a key challenge for the successful transformation of agrifood systems and must be an integral component of research, planning and implementation of measures to drive circularity in agrifood systems. A failure to properly address food safety could be detrimental to sustainability targets and lead to outbreaks of foodborne illnesses, eroding public confidence.

BOX 2

FOOD SAFETY CONSIDERATIONS FOR CREATING A CIRCULAR ECONOMY FOR PHOSPHORUS

Soil phosphorus is a critical nutrient for plant growth and is crucial for maintaining soil fertility, particularly in intensive industrialized farming systems. In addition, phosphorus in plants is an important dietary nutrient for humans and livestock.

Mineral phosphate rock, taken from sedimentary or igneous deposits, which accounts for almost all the feedstock for agricultural fertilizers, is a finite resource. Estimates of the lifetime of phosphorus reserves vary widely, from 60 to 400 years (Cordell, Drangert and White, 2009; Cordell and White, 2011). A considerably more pressing concern, however, is that the production of phosphate fertilizer relies on the inexpensive supply of sulphur derived from oil and natural gas to produce sulphuric acid (Day, Alexander and Maslin, 2023). The decarbonization of economies, resulting in a reduced supply of sulphur, and competing demands for sulphuric acid used in manufacturing materials for renewable energy production and storage will impact on the price and supply of phosphate fertilizer.

A great deal of phosphate rock is wasted in fertilizer production and use in agrifood systems. It is estimated that 80 percent of the phosphorus in exploited reserves does not reach the human diet, as it is lost throughout all stages of its processing and use, including during fertilizer production, leaching from fertilized soils and from unutilized phosphate in manure and crop and food wastes (Cordell, Drangert and White, 2009). Given the need for phosphorus-based fertilizers to ensure global food security, fertilizer production and use must be made more sustainable. Building a circular economy for phosphorus has the potential to reduce wastage in fertilizer production, reduce water runoff and consequent phosphorous losses, favour the recycling of phosphorous and reducing food waste. Circular practices for phosphate may include recovery from alternative sources such as wastewater and recycling by-products, such as phosphogypsum, for use in fertilizers or animal feed supplements (Chernysh *et al.*, 2021).

Accessing these new sources of phosphate presents a changed risk profile for food safety. Mined phosphate fertilizers are commonly reported to be contaminated with heavy metals, such as cadmium, which present long-term accumulation risks in agricultural soils and dietary exposure through uptake into crops and animals (Järup and Åkesson, 2009). For recycled phosphate sources, such as struvite from human and livestock wastewater, studies suggest cadmium and other heavy metals are a lower risk. However, there is a risk of carryover of pharmaceuticals, such as tetracycline, as well as copper and zinc (Kemacheevaku *et al.*, 2012; Ruy and Lee, 2015). Less refined phosphate sources, such as wastewater sludge and biosolids, contain a broad range of microbiological and chemical contaminants. These phosphate sources present a varied risk profile for food safety, depending on the source and level of treatment (Wolters *et al.*, 2022). It is necessary to fully understand the different food safety hazards related to alternative phosphate sources to ensure that food remains safe while transforming agrifood systems away from mined mineral sources.

Source: See References.

1.6 USING FORESIGHT IN FOOD SAFETY TO TRANSFORM TO CIRCULAR AGRIFOOD SYSTEMS

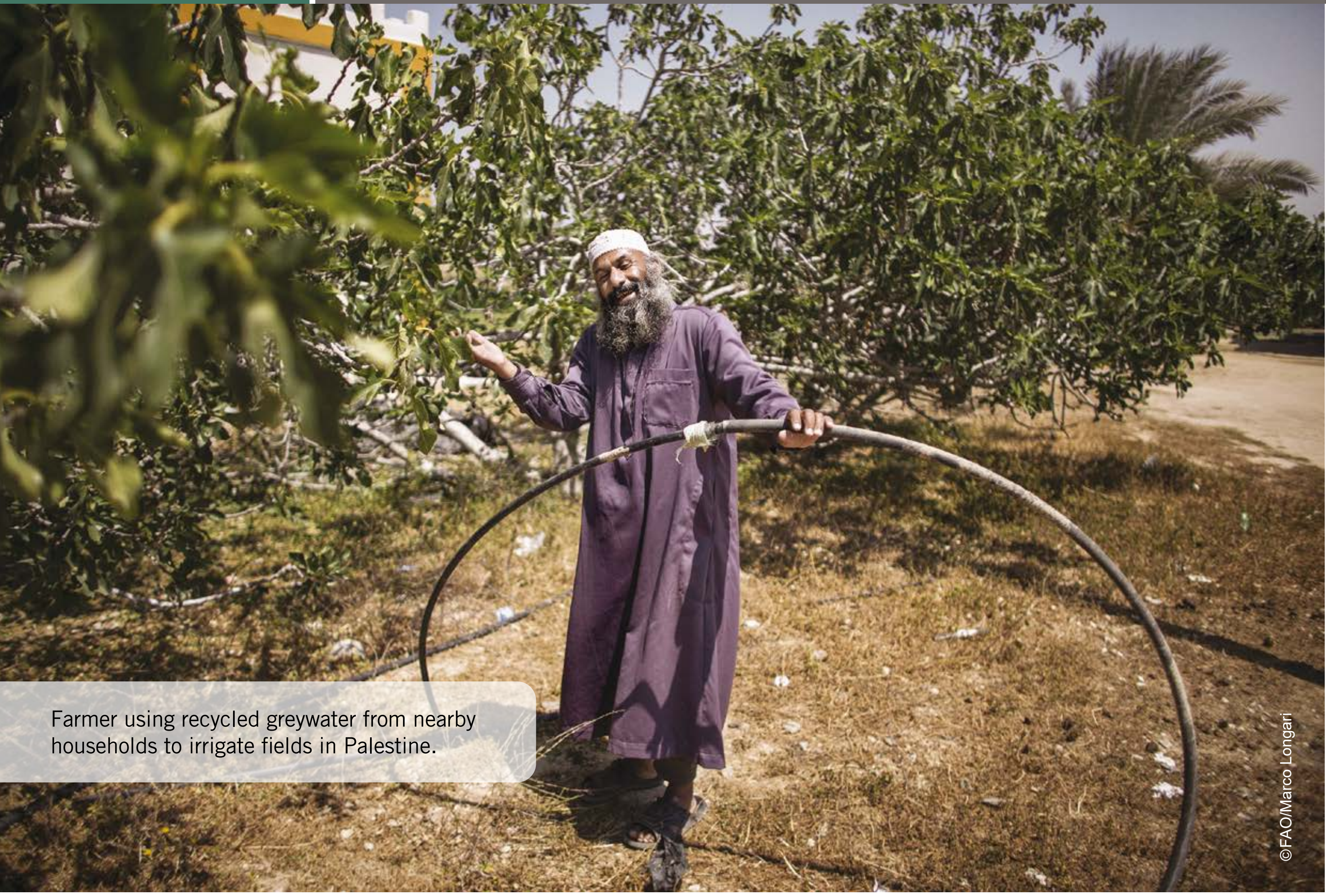
Globally, a wide range of initiatives are underway that aim to transform our current linear agrifood systems to closed-loop systems. The results of these initiatives may have implications for food safety and foresight methodologies (Box 3), allowing the exploration of these possible implications to determine the best course of action to navigate challenges while optimizing benefits. The purpose of this foresight report is to consider the current and emerging evidence related to food safety risks in various circular production initiatives within agrifood systems. Addressing the critical importance of food safety in agrifood systems transformation, this report considers the literature on policies and practices presented as solutions to address the four areas of interest in agrifood-system sustainability: water scarcity, food waste, food packaging waste, and land use efficiency. The case studies presented throughout the report highlight food safety risks when circular processes have been adopted across different countries and, where relevant, the actions that were taken to mitigate these risks. Finally, the report discusses some policy recommendations to support the transformation to circular and safe agrifood systems.

BOX 3

WHAT IS FORESIGHT?

Foresight involves taking a systematic, medium- to long-term view of the future to appropriately guide present-day decisions. How agrifood systems are transformed over the coming decades will have profound implications for food safety – and for our health, economic and social wellbeing, and the environment. Consequently, it is critical to keep pace with the changes within agrifood systems. Foresight can help us understand how new trends, changes or knowledge gaps can affect agrifood systems in general, and food safety in particular (FAO, 2022a). Preparing for how the future might unfold will enable us to better respond to risks as well as optimize opportunities. Foresight can help bridge science and policy by utilizing a long-term thinking approach to inform a range of food chain-related decisions and help ensure that food remains safe, regardless of the forms of production and processing it undergoes. FAO has extensive expertise and knowledge and a network that spans the agrifood sector worldwide. From this unique position, FAO is well placed to gather insights and information and support countries in doing so, as well as disseminate food safety intelligence to stakeholders and provide proactive and strategic guidance at the global, regional and national levels.

Source: **FAO (Food and Agriculture Organization of the United Nations).** 2022a. *Thinking about the future of food safety – a foresight report.* Rome. https://www.fao.org/documents/card/en/c/cb8667en



Farmer using recycled greywater from nearby households to irrigate fields in Palestine.

©FAO/Marco Longari

An employee working inside a fresh hydroponics farm in Maldives.

©FAO/Ishara Kodikara

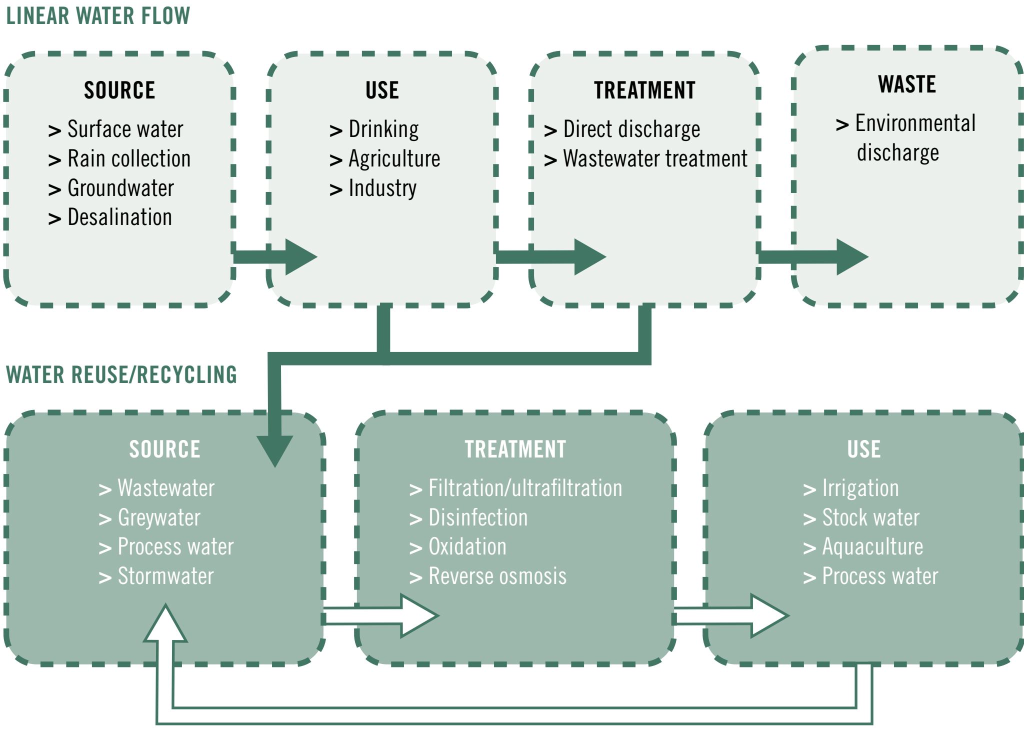
CHAPTER 2

WATER RECYCLING AND REUSE

The Earth's water resources must be sustainably managed to ensure the supply of safe drinking water and water resources needed for economic growth amid a changing climate. A circular economy for water means increasing water use efficiency. Reusing and recycling water can benefit the agrifood system in several ways. For instance, recycling drainage water from agricultural fields will provide a supplemental water source for irrigation as well as reducing nutrient loading and sediment flow into downstream water bodies (Moursi *et al.*, 2023). Water recycling for agricultural use is well established in some regions. For example, in California, where water recycling has been in place since the early twentieth century, an estimated 319 million m^3 of recycled water was used in agriculture in 2009 (Olivieri *et al.*, 2014). In other places, the change is more recent. In 2017, Malta introduced the New Water programme, under which wastewater treatment facilities were upgraded with polishing plants (with ultrafiltration, reverse osmosis and advanced oxidation processes) to supply water for agricultural use (Water Service Corporation, 2017). In 2021, 1.4 million m^3 of recycled water was supplied for agriculture in Malta (Water Service Corporation, 2021).

Alternative water sources include untreated sewage (also called blackwater), water used for bathing and washing (greywater), water from industrial processes and surface runoff (stormwater), all of which require treatment before use (see Figure 1). Drawing on these alternative sources provides a localized water supply to support agricultural systems, particularly in peri-urban and urban areas. Recycled urban water can be used, for instance, for home or community gardens or for indoor or rooftop farming (Suman and Bhatnagar, 2019). Such production systems provide opportunities to reduce costs for transporting food from rural to urban regions and reduce pressure on local water supplies, while maximizing land use for food production. Indeed, water scarcity has been identified as a notable barrier in establishing peri-urban and urban agricultural systems, underscoring the need for water recycling or reuse measures (Follmann *et al.*, 2021). Furthermore, alternative waters can also serve as an input for recharging environmental water sources and consequently, are reused in agricultural systems. For example, recharging groundwater aquifers using alternative waters is undertaken through managed infiltration basins replicating natural recharge processes or through direct recharge where wells are used to inject water into the aquifer (Casanova, Devau and Pettenati, 2016). Ensuring water quality in these systems can be achieved using natural filtration processes or by replacing or augmenting these processes with treatment.

FIGURE 1. **COMPARISON BETWEEN LINEAR WATER FLOWS AND CIRCULAR PROCESSES FOR REUSE AND RECYCLING OF WATER IN AGRIFOOD PRODUCTION**



Another option for recycling water in agrifood production systems is through vertical farming, that is, aquaculture, aquaponics or hydroponic crop production in vertically stacked layers. These farming systems offer advantages for maximizing productivity in a smaller land footprint. As vertical farms can be developed in underutilized urban settings, they offer the potential to reduce transport costs and food waste by allowing food to be supplied from within urban neighbourhoods. High water efficiency in vertical farming can be achieved with closed-loop water recirculation through the vertical layers (Kalantari *et al.*, 2018), which also enables nutrient recycling and minimizes the discharge of wastewater. Technological developments in water capture, such as atmospheric water generation, offer the potential to facilitate vertical farming and other controlled-environment agricultural systems in areas where water is scarce (Zhao *et al.*, 2022). Future advances in food production, such as cultured meat production, also offer the potential to recycle water and associated growth media in a circular loop or into other agrifood production (Myers *et al.*, 2023).

Given the range of benefits they offer, water recycling and reuse will likely become more important as water stress increases. Depending on the source of the reused or recycled water, however, there are several potential food safety risks. Many studies have analyzed the contaminants in soil and produce resulting from using untreated sewage water for agricultural production and the associated risks (Lesser *et al.*, 2018; Amahmid, Asmama and Bouhoum, 2022).

The use of treatment processes, for example separation of sludges, oxidation and chlorination, can reduce the contaminants persisting in recycled water. This could include contaminants sequestering into the solid fraction, being degraded through oxidation processes, or in the case of pathogens, reducing their viability. For example, in water treatment processes for pathogens, log reductions up to 6.5 to 7.0 are achievable through filtration, while primary disinfection often achieves log reductions of 2 for chlorine and ozone and up to 4 through ultraviolet (UV) treatment (FAO and WHO, 2021).

Aside from recycling the liquid fraction of wastewater sources, the solid fraction, commonly termed sludge or biosolids, is also a potential feedstock in circular agrifood systems that adds beneficial nutrients and organic matter to soils (de Amorim Júnior *et al.*, 2022).

2.1 PATHOGEN AND CONTAMINANT OCCURRENCE IN ALTERNATIVE WATER SOURCES

2.1.1 PATHOGENS

The microbial quality of irrigation water, stock drinking water or food processing water used in agrifood systems is an important factor for determining the risk of dietary exposure and resulting foodborne illness. Acknowledging the importance of characterizing and validating the safety and quality of water, the Joint FAO/WHO Expert Meeting on Microbiological Risk Assessment (JEMRA) has developed technical reports on assessing fit-for-purpose water for food production and specifically for water use and reuse in the fresh produce, dairy, and fish and fishery product sectors (FAO and WHO, 2021, 2023a, 2023b). Supported by literature reviews and case studies, these technical reports provide guidelines for comprehensive hazard identification for pathogens of potential concern in water sources. A case study from these reports is presented in the policy considerations section.

Irrigation with pathogen-contaminated water is a known pathway for microbial contamination of crops (Alegbeleye, Singleton and Sant'Ana, 2018). The use of untreated sewage to irrigate crops has been implicated in a range of disease outbreaks from retail produce (Adegoke *et al.*, 2018). Without a multi-barrier treatment approach, wastewater treatment may not sufficiently reduce pathogens, meaning a microbial risk remains in the reclaimed wastewater (Sano *et al.*, 2016; Gerba, Betancourt and Kitajima, 2017). Pathogens, including bacteria, viruses, protozoa and helminths, are a key concern as they are excreted at high rates by infected individuals into human and animal wastewaters and survive for long periods in the environment. Protozoal species such as *Cryptosporidium*, *Giardia* and *Cyclospora*, are reported to be resistant to removal techniques (Kitajima *et al.*, 2014; Suarez *et al.*, 2022), while reduction of *Dientamoeba fragilis* in wastewater treatment effluent was reported at only 20 to 34 percent (Berglund *et al.*, 2017). Similarly, human viruses, including norovirus, enterovirus and adenovirus, are abundant in municipal wastewaters and present risks for water reuse due to their small size and resistance to disinfection, and since consuming only a small number of viral particles can lead to infection (Jiang *et al.*, 2022).

Hepatitis A and hepatitis E viruses have also been reported to transfer to treated wastewater, which presents a particular concern in highly endemic areas (Takuissu *et al.*, 2022, 2023). Pathways for fungal pathogens, or mycotoxin producers, through recycled water are poorly characterized; however, they may be an emerging risk as they aren't typically assessed with other microbial criteria (Short *et al.*, 2022).

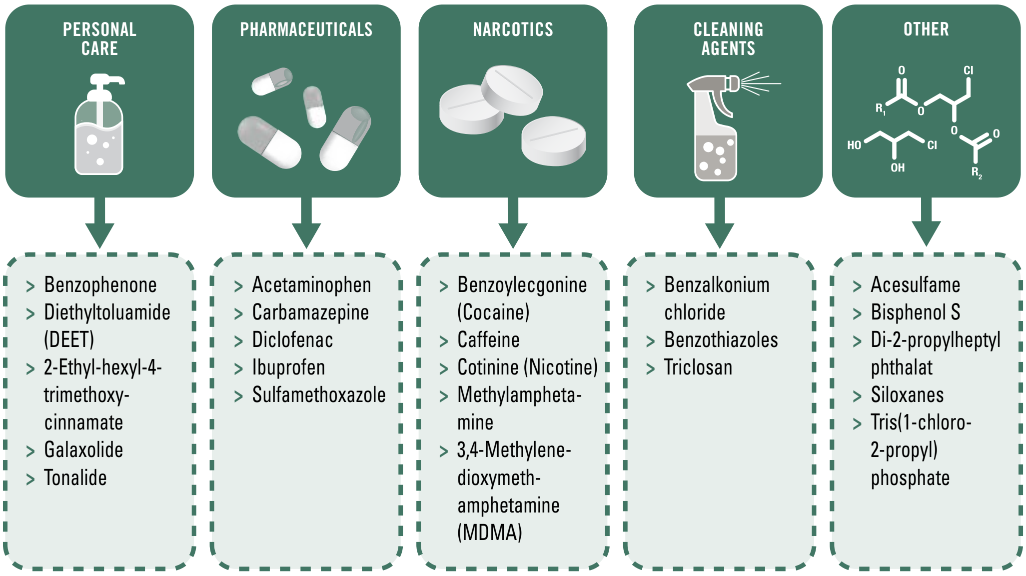
Recycled water, for instance from urban greywater, and reusing process water from agriculture and industry, may also be a source for faecal pathogens. For example, household greywater still commonly contains faecal contamination, such as from washing soiled clothes, that present a potential source for crop contamination (Finley *et al.*, 2009; Natural Resource Management Ministerial Council, Environment Protection and Heritage Council and Australian Health Ministers' Conference, 2006). A study of *Escherichia coli* in greywater sources from different household and commercial origins found that shower water was in the lowest water quality categories, severely restricting its potential reuse in agriculture without further treatment (Garnett, 2019).

Even without evident human or animal waste sources, microbial risks remain. For example, stored water comprising of water used to wash produce and runoff from a processing area had prevalence of *Salmonella* spp. and *Listeria monocytogenes* (Sharma *et al.*, 2020). Water used to clean contact surfaces for raw foodstuffs may be cross-contaminated. Raw milk, for example, can contain *Salmonella* spp. and Shiga toxin-producing *E. coli* (FAO and WHO, 2023a). Aquatic microbial pathogens such as *Vibrio* spp. are indigenous in environmental waters and cross-contaminate process water from contaminated seafood (FAO and WHO, 2023b). The microbial risk of process water from other food manufacturing stages varies and will often be specific to the manufacturing facility and the food production processes generating the water. A case study on the qualitative risk assessment of the recirculation of cooling water in cheese manufacturing reported a very low likelihood but severe risk of *L. monocytogenes* from cross-contamination (FAO and WHO, 2023a). Another study examining reclaimed water from cheese whey after membrane filtration use in milk industry cleaning-in-place systems concluded it would result in a minimal increase in annual cases of listeriosis for at-risk populations (Dogan *et al.*, 2020).

2.1.2 CHEMICAL CONTAMINANTS

The occurrence of chemical contaminants in recycled or reused water is another area of concern for food safety. For human wastewater origin sources, the focus is typically placed on personal care products, cleaning chemicals, pharmaceuticals and narcotics that, through direct addition or human excretion, result in appreciable concentrations in household wastewater (van Asselt *et al.*, 2022). In recent years, improvements in analytical technology have led to an extensive range of these emerging contaminants being quantified in wastewater (Figure 2).

FIGURE 2. **EXAMPLES OF EMERGING CONTAMINANTS IN HOUSEHOLD WASTEWATER**



Sources: Dos Santos, Hoppe-Jones and Snyder, 2019; Styszko *et al.*, 2020; Vasilachi *et al.*, 2020; Parida *et al.*, 2021, Xu *et al.*, 2021; Barber and Hartmann, 2022.

Wastewater from agricultural sources also regularly contains excreted residues from veterinary medicines, fertilizers and pesticides (OECD, 2012; van Asselt *et al.*, 2022; Rad, Ray and Barghi, 2022). Alternative water sources derived from, or subject to, inputs from nutrient-rich agriculture wastes or other wastewaters, may also lead to eutrophic conditions in which cyanobacterial blooms form. In these conditions, biosynthesized cyanobacterial toxins, such as microcystins, can be released and persist in the recycled water (Romanis, Pearson and Neilan, 2021; Melaram, Newton and Chafin, 2022). Even water reused in closed systems can suffer contamination from the inputs in these systems. For example, water reuse containment ponds in ornamental systems have reported paclobutrazol as a water-quality concern, resulting from in-system use as a plant growth regulator, highlighting the potential for any chemical inputs to persist in hydroponic closed loops (Ristvey, Belayneh and Lea-Cox, 2019).

A further consideration is that in many countries wastewater facilities accept inputs from a variety of industries as well as landfill leachates, hence a range of other contaminants are often present in influent, rendering the treated water unusable for different applications. For example, wastewater from car washing is reported to contain levels of heavy metals and polycyclic aromatic hydrocarbons (PAHs) (Qamar *et al.*, 2017, Illoms *et al.*, 2020) and difficult-to-treat textile dyes are a concern for textile industry wastewater (Al-Tohamy *et al.*, 2022). Similarly, the presence of urban stormwater in recycled water is a potential source of heavy metals, commonly zinc, copper and nickel, and organics such as PAHs and pesticides (Masoner *et al.*, 2019). Aside from direct food safety risks, urban waters may occasionally have high salinity or contain residues from chemicals used in home and business pest control and grounds maintenance, which present issues for crop yield and potential rejection by livestock (Tang *et al.*, 2013).

Sludges from wastewater treatment typically have a comparable risk profile to recycled wastewater, with the exception that sludge favours the build-up of chemical contaminants partitioned to the solids and organic matter (Berthod *et al.*, 2015). Volatile methylsiloxanes, common consumer chemicals, have been reported to persist in sludge-amended soils and transfer in trace levels to peas grown *in situ* (Fernandes *et al.*, 2022). Similarly, organophosphate ester flame retardants, such as tris(1-chloro-2-propyl) phosphate (TCPP), are reported as common in wastewater sludges and have appreciable bioconcentration factors from treated soil to crops (Bester, 2005; Eggen *et al.*, 2013, Pang *et al.*, 2016). Lastly, wastewater sludges are reported to contain microplastics, which transfer into agricultural soils after application (Huang, Mohamed and Li, 2023).

In water source recharge schemes, such as direct aquifer injection and managed aquifer recharge, there are concerns about the occurrence of pathogens and contaminants in the recharge water (Cassanova, Deveau and Pettenati, 2016). Although dilution and natural attenuation of pathogens and contaminants in the water source may occur during infiltration and transport, there is still a risk that these may persist to abstraction points for agricultural water, reducing the quality of the water (Imig *et al.*, 2022). Further risks include the occurrence of disinfection by-products resulting from water treatment, changes to aquifer chemistry and mobilization of natural contaminants.

2.1.3 ANTIMICROBIAL RESISTANCE GENES

The potential presence of both human pathogens and pharmaceuticals or biocides in recycled or reused water presents a potential concern area for antimicrobial or biocide resistance. Studies of recycled water sources have shown broad prevalence of ARGs. For example, tertiary treated wastewater and vegetable processing water contained ARGs coding for resistance to macrolide, lincosamide, elfamycins, aminoglycosides, rifampin and steptogramin (Malayil *et al.*, 2022). The occurrence of ARGs in recycled water, particularly those for clinically used antibiotics, presents a potential risk if they are transferred though horizontal gene transfer to human pathogens and confer resistance to treatment (Zhang *et al.*, 2021).

2.2 ASSESSMENT OF FOOD SAFETY RISKS IN WATER RECYCLING OR REUSE

2.2.1 MICROBIAL FOOD SAFETY RISKS

The specific risk to food safety posed by pathogens will differ depending on how the reused or recycled water is used in cropping, animal rearing or food production. For irrigation, prolonged contact of the reused or recycled water with the edible parts of crops, particularly those eaten raw, is seen as the highest risk (Stine *et al.*, 2005; FAO and WHO, 2021), although subsurface drip irrigation minimizes the percentage transfer to edible components and consequently, could employ lower-quality water (Tripathi *et al.*, 2015; FAO and WHO, 2021). European requirements for drip irrigation using recycled water differ depending on the distance of the produce from the ground, with the highest quality water (Class A: *E. coli* <10 cfu/10 ml) required for root crops, while lower quality water can be used for fruit trees (Class C; *E. coli* <100 cfu/100 ml). There is uncertainty over the potential for root uptake of viruses (norovirus and hepatitis A virus) from soil or in hydroponic systems using inoculated water (Bundesinstitut für Risikobewertung [BfR], 2022a). A recent study reported internalization in carrots and tomato of enterovirus and norovirus GI through soil to root uptake of chlorine-treated wastewater (Fernandes *et al.*, 2023).

In crops and produce that are to be further processed or cooked, the microbial risks are lower and treatment requirements for water are commonly reduced (FAO and WHO, 2021). For example, the Australian state of Victoria places requirements on recycled water for use with crops to be eaten raw (Class A water) to have 6-$\log_{10}$ reduction in bacteria and protozoa and 7-$\log_{10}$ in viruses. Recycled water for use in cooked or processed food crops and crops not directly exposed to the water (Class C) requires secondary treatment and pathogen reduction to a median *E. coli* indicator level of <1000 org/100 ml (Environment Protection Authority Victoria, 2021; 2022). In food establishments, recycled water for food contact needs to be equivalent to potable water quality while lower quality water is often fit for purpose in non-contact roles, for example in closed-loop heat-transfer systems (FAO and WHO, 2019a).

There are limited permissions and supporting studies on the microbial risks of using recycled water as a drinking source for livestock (stock water). Hepatitis E virus presents a potential risk in recycled stock water as pigs are reported to be a reservoir of zoonotic strains, which can be transmitted to humans through contaminated pork (Ahmed and Nasheri, 2023).

Australian guidance focuses on helminths as a key risk, given the potential for these to transmit to livestock, constituting a food safety risk through the consumption of undercooked meat (Natural Resource Management Ministerial Council, Environment Protection and Heritage and Council Australian Health Ministers' Conference, 2006). Consequently, the use of recycled water derived from human wastewater is prohibited for pigs, due to the neurocysticercosis risk from completion of the tapeworm *Taenia solium* life cycle (Environment Protection

Authority Victoria, 2021). While recycled water is permitted for cattle, it requires treatment to approximately 4-$\log_{10}$ removal of helminth ova to manage the risk of *Taenia saginata*, as well as meeting an *E. coli* quality objective of <100 org/100 ml. A recent report by FAO and WHO (2023a) focusing on dairy processing identified that risk assessment methods for determining fit-for-purpose water reuse in dairy processing would be equally transferable to on-farm dairy production water reuse. The experience from California on risk assessment of recycled water as a drinking source for livestock is outlined in Box 4.

Although strict requirements for helminths are retained, the microbial risks of recycled water for irrigation of feed crops and pasture are generally approached as a lesser risk to stock-drinking water (EC, 2020). However, dairy animals are commonly treated separately, either being excluded or required to have greater exclusion periods from irrigated areas due to the direct risk of contaminating udders (Natural Resource Management Ministerial Council, Environment Protection and Heritage Council Australian Health Ministers' Conference, 2006).

The use of recycled water in aquaculture has been implemented in several countries over many years, given the benefits of recovering nutrients and managing waste (Edwards, 1992). Aquatic systems are also at a higher risk of unintentional contamination with untreated sewage. Consequently, there is a general understanding of this risk. A recent review completed a risk ranking of waterborne biohazards occurring in recycled or reused water sources that are of relevance to the safety of fish and fishery products (FAO and WHO, 2023b). The review concluded that there was insufficient evidence regarding the safety of using treated municipal wastewater for fish farming. Typically, faecal contaminants such as *E. coli* and *Salmonella* spp. are present in fish intestinal contents and skin, but are generally much reduced in muscle; however, this does present a cross-contamination risk in processing (Dang and Dalsgaard, 2012; Mark *et al.*, 2019). *Vibrio cholerae* was reported to be present in fish raised in wastewater stabilization ponds, as well as vegetables irrigated with this water, suggesting a potential risk in cholera-endemic areas (Hounmanou *et al.*, 2016). In relation to food safety risks, WHO (2006) recommends a bacterial guideline of a mean 10 000 *E. coli*/100 ml for fish-pond water, and no detected viable trematode eggs/100 ml.

Recycling water in a closed loop in vertical farming and other forms of controlled-environment agriculture emphasizes the importance of water quality to avoid contamination with pathogens, which evidence indicates spread and multiply rapidly (Shaw *et al.*, 2016). A range of studies report the transmission of pathogens to hydroponically grown vegetables, including via internalization, which is often difficult to treat post-harvest (Sela Saldinger *et al.*, 2023). Further foodborne illness outbreaks have been associated with leafy greens, with contamination arising from water use and growth media, including from *Salmonella* Typhimurium (US FDA, 2021). The Department of Agriculture of the United States of America (USDA) has good agricultural practice requirements for aquaponics (USDA, 2022). These include not housing fish and plants in the same tanks, filtering fish tank water before it is recycled into hydroponics and sanitizing if the water is likely to contact edible crop portions, and conducting at least monthly testing with no detectable *E. coli*/100 ml of water, where the root system is packaged with the crop for sale. However, despite the growing interest in the potential for using recycled wastewater in controlled-environment agriculture, a current review of aquaponics found limited research on food safety risks stemming from reclaimed water for either the aquatic organisms or plant species in these systems (Cifuentes-Torres, Correa-Reyes and Mendoza-Espinosa, 2021).

BOX 4

ASSESSMENT OF RECYCLED WATER USED FOR LIVESTOCK IN CALIFORNIA

California's agricultural production is heavily threatened by water scarcity. The 2012–2016 drought, 2014–2015 being the most severe years, was estimated to have caused crop revenue losses in the amount of USD 1.7 billion (Lund *et al.*, 2018). Using recycled water for agricultural crop irrigation is permitted as a suitable alternative to groundwater or surface water. Supporting this are Water Recycling Criteria (California State Water Resources Control Board, 2018) that outline specific filtration and disinfection requirements to manage pathogen risks, defining the resulting product as disinfected tertiary recycled water.

Livestock animal products (including milk, beef, pork, and eggs) accounted for 27 percent of California's agricultural revenues during this period. In 2015, it was estimated that approximately 160 000 beef cattle were being reared in a region rated as abnormally dry. With animals requiring higher daily water intake in the hottest weather, there was a need to provide safe and reliable water supplies for livestock. Although permitted for irrigation, the Water Recycling Criteria did not specifically address the use of recycled water for livestock drinking water (Poppenga *et al.*, 2018).

An independent advisory panel was convened to assess whether using disinfected tertiary recycled water as stock water for non-dairy animals would pose a significant risk to public and animal health (Poppenga *et al.*, 2018). Risks were modelled considering exposure pathways for pathogens, including antimicrobial-resistant strains and chemical contaminants from both consumption and direct animal handling. It was concluded, based on conservative estimates, that chemical contaminant impacts to food safety and the quality of meat and eggs were unlikely, although there was uncertainty over the potential for these to directly impact livestock health. However, microbial quality was a concern for animal health, and potentially for pathogens such as hepatitis E virus, for which a pathway exists to cause food safety concerns in pork (albeit a lack of dose-response models in animals limited any detailed modelling). The panel concluded that there was insufficient evidence to determine if the use of disinfected tertiary recycled water for non-dairy stock water would present a risk to public health, primarily as a result of the uncertainty related to pathogens. Among the recommendations were that the use of disinfected tertiary recycled water for stock water should have a targeted source-control programme to exclude high-risk wastewater inputs (such as abattoir waste, zoo waste and concentrated industrial inputs), as well as additional UV and chemical disinfection requirements.

Sources: **California State Water Resources Control Board**. 2018. Title 22, California Code of Regulations. In: California State Water Resources Control Board. *Regulations Related to Recycled Water.* 1 October 2018. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/lawbook/RWregulations_20181001.pdf

Lund, J., Medellin-Azuara, J., Durand, J. & Stone, K. 2018. Lessons from California's 2012–2016 Drought. *Journal of Water Resources Planning and Management,* 144(10).

Poppenga, R., Ashbolt, N., Mikolon, A., Pecson, B., Rock, C. & Smith, D. 2018. *Using Disinfected Tertiary Recycled Water for Non-Dairy Livestock Watering: A Human and Animal Health Evaluation for the State of California*. Independent Advisory Panel Final Report. California, USA, National Water Research Institute.

2.2.2 CONTAMINANT FOOD SAFETY RISKS

The science on food safety implications for emerging contaminants in recycled or reused water is still developing. Generally, risks of uptake into cropping plants will depend on the persistence, partitioning and mobility of the chemical in soil systems and the efficiency of root uptake (OECD, 2012). Antibiotics (Zhang *et al.*, 2017; Al-Farsi *et al.*, 2018), benzophenone UV filters (Sunyer-Caldú *et al.*, 2022) and sweeteners (Kreuzig *et al.*, 2021; Manasfi *et al.*, 2021) are contaminants reported to accumulate in produce. The anticonvulsant drug carbamazepine is one of the more studied emerging contaminants and has been reported in field trials to be concentrated from wastewater-effluent-treated soil or hydroponic media into a range of different fruit and vegetable crops (Franklin *et al.*, 2016; Ben Mordechay *et al.*, 2018; González-García *et al.*, 2018; Picó *et al.*, 2019; Beltrán *et al.*, 2020; Ben Mordechay *et al.*, 2022). However, uptake of other substances such as ibuprofen is reported to be minimal (Al-Farsi *et al.*, 2018; García and Fernández-López, 2022) and uptake of bisphenol A, octyl- and nonylphenol into wheat and vegetables is not significantly different between ground or reclaimed water sources for irrigation (Li *et al.*, 2021). Further examples of contaminants in home gardens irrigated with treated wastewater are provided in Box 5. Although food-chain uptake to levels equivalent to prescribed doses or household concentrations is unlikely (Fu *et al.*, 2019), the potential produce uptake emphasizes the importance of evaluating water sources for potential risk of emerging contaminants.

Evidence is also emerging of the potential role irrigation using recycled water plays in the contamination of soil with microplastics (Garrido Gamarro and Costanzo, 2022; Pérez-Reverón *et al.*, 2022). Even with high efficiencies of removal, some micro- and nanoplastics are reported to pass through wastewater treatment and transfer to recycled water used for crop irrigation (Garrido Gamarro and Costanzo, 2022). Our understanding of the potential for plant uptake of nanoplastics is developing, albeit with considerable research gaps on the accumulation in food commodities (Azzem *et al.*, 2021; Garrido Gamarro and Costanzo, 2022). Our current understanding of the food safety risks from micro- and nanoplastics is limited. For example, while direct exposure to microplastics is not presently anticipated to be a health risk, they often contain chemical components that may migrate into food (Garrido Gamarro and Costanzo, 2022; Rubio-Armendáriz *et al.*, 2022).

Cyanobacterial toxin transfer from contaminated irrigation water to crops is an area of emerging concern with studies reporting the accumulation of microcystins in different fruit, vegetable and grain crops (Mutoti, Gumbo and Jideani, 2022) and cylindrospermopsins into leafy vegetables (Cordeiro-Araújo, Chia and Bittencourt-Oliveira, 2017). Data reviewed by the WHO regarding cyanobacterial toxin occurrence in crops did not infer high levels of short-term exposure were occurring but did raise the concern that use of water with higher levels of toxins could present greater risks to health, particularly if applied to staple foods, and recommended screening for toxin concentrations (Ibelings, Foss and Chorus, 2021).

Finally, heavy metals commonly occur in recycled water, with contaminants such as chromium and cadmium elevated in recycled water-irrigated crops (Abi Saab *et al.*, 2022). Several studies report that the dietary risk from heavy metals in recycled irrigation water is generally low, as levels in produce typically fall within acceptable dietary levels; however, this may not be the case for all recycled water sources and irrigation systems (Qureshi *et al.*, 2016; Hussain, Priyadarshi and Dubey, 2019, Abi Saab *et al.*, 2022).

Risks to livestock production systems from emerging contaminants in reused or recycled water used for stock water and feed/pasture irrigation are poorly characterized. The environmental contaminants of particular concern for meat and other tissue contamination are those with appreciable lipophilicity, allowing for bioaccumulation. Emerging contaminants present in wastewater from personal care products and pharmaceutical use generally have low lipophilicity, high solubility and high excretion rates. Consequently, the risks of bioaccumulation into edible tissues are less likely. Exceptions are chlorinated organophosphate flame retardants (for example, TCPP), which have been reported in animal products, including milk and eggs, in several countries (Li *et al.*, 2019). Given the range of possible sources for chlorinated organophosphate flame retardants and poor elimination through wastewater treatment, they are likely to be present in recycled wastewater (Meyer and Bester, 2004).

Considering the risks from the use of reused or recycled water in aquaculture or aquaponics systems, there is little direct reporting of risks from contaminants. However, monitoring of aquaculture waters where wastewater may have entered the system has shown the occurrence of a wide variety of emerging contaminants, including per- and polyfluorinated alkyl substances (PFAS), pharmaceuticals, anticorrosion inhibitors and narcotics (Lai *et al.*, 2018). Certainly, evidence from wild-caught fish indicates the potential for these substances found in wastewater to be retained in fish tissues (Deere *et al.*, 2020), although one comparative study suggested that the contamination risk in farm-raised fish is lower than in wild-caught fish (Henríquez-Hernández *et al.*, 2017).

BOX 5

HOME-GARDEN IRRIGATION WITH TREATED WASTEWATER

Reclaimed treated wastewater from the Hyrum wastewater treatment plant in Utah, United States of America is used to supplement non-potable irrigation water for home gardens. A comprehensive study of the risk for home vegetable gardens was conducted by testing for the presence of pathogens and personal care contaminants in different produce typically consumed raw (Weidhaas *et al.*, 2022).

Pathogen genomic material was regularly reported through quantitative polymerase chain reaction (qPCR) testing of the garden produce, with genetic material from *E. coli* (*uidA*) and enterococci (23S rRNA) being most common (present in over 80 percent of the samples). *Salmonella* spp. (*invA*) and enteric adenovirus were reported in 40 to 42 percent of the samples and norovirus was reported in 17 percent of the samples. Of the personal care contaminants, the pharmaceuticals carbamazepine, fluoxetine, progesterone and sulfamethoxazole were most commonly reported up to concentrations of 11 to 64 µg/kg.

BOX 5 (cont.)

HOME-GARDEN IRRIGATION WITH TREATED WASTEWATER

The insect repellent *N,N*-diethyl-meta-toluamide (diethyltoluamide, DEET) and caffeine were only present in 4 out of the 66 samples tested, while the cleaning agent triclosan and the flame retardant tris-(2-chloroethyl) phosphate were not detected, despite their presence in the reclaimed water.

A risk assessment of the results indicated that personal care contaminants were of little concern, and even drinking the irrigation water directly was not assessed as a concern, although it was acknowledged that the tested suite was limited and excluded other contaminants that enter wastewater, such as per- and polyfluorinated alkyl substances (PFAS). In contrast, quantitative microbial risk assessment identified that residents consuming their home garden produce for more than 90 days would have a higher probability of pathogen-related illness than the national benchmark, with the greatest risk arising from adenovirus and enterococci. An additional concern was the presence of multiple families of antibiotic resistance genes (ARGs) on the produce, potentially associated with the co-occurrence of ARGs with antibiotics (Weidhaas *et al.*, 2022).

Community surveys in two cities of northern Utah identified that the perception of possible health risks arising from the use of treated wastewater for irrigation was low (Flint and Koci, 2020). Consequently, a key recommendation was greater outreach to advise on the correct washing of produce before consumption.

Sources: **Flint, C.G. & Koci, K.R.** 2021. Local resident perceptions of water reuse in Northern Utah. *Water Environment Research*, 93:123–135.

Weidhaas, J., Olsen, M., McLean, J.E., Allen, N., Ahmadi, L., Duodu, K. & Dupont, R. 2022. Microbial and chemical risk from reclaimed water use for residential irrigation. *Water Reuse*, 12(3):289.

Experts test water samples
for contamination, Cook Islands.

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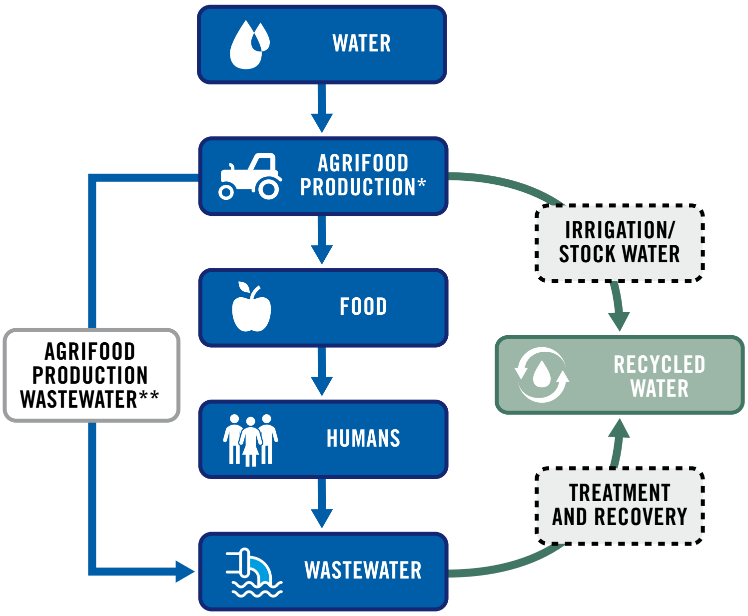
FIGURE 3. **LINEAR AND CIRCULAR MODELS OF WATER RECYCLING AND REUSE IN AGRIFOOD PRODUCTION**



Notes: **Blue** boxes and lines reflect the existing linear processes. **Green** boxes and lines represent circular processes. **Grey** boxes detail the processes in use.

* All water used for making food (irrigation, feeding animals, cleaning equipment, processing etc.).

** For example, sewage from slaughterhouse.

Spoiled tomatoes at a market in Egypt.

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Farmer collects black soldier fly larvae to feed fish, Kenya.

©FAO/Eduardo Soteras

CHAPTER 3

FOOD LOSS AND WASTE

The significance of food waste as a global concern related to agrifood systems sustainability and food security is reflected in a specific target under SDG 12 (Ensure sustainable consumption and production patterns). Target SDG 12.3 is to “halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses” by 2030 (UN, 2015). In support of this target, the FAO Voluntary Code of Conduct for Food Loss and Waste Reduction presents guiding principles and actions for countries to address the causes of food loss and waste (FAO, 2022b). All measures to reduce food loss and waste must consider food safety and nutritional requirements. Goossens, Wegner and Schmidt (2019) propose four categories of measures to prevent food waste; potential food safety implications must be considered in each of these themes.

Avoidance: Managing food waste at source by reducing surplus and managing overproduction. Generally, avoidance focuses on managing supply rather than measures to introduce alternative pathways for food waste, and as a result, this does not impact on food safety beyond the impacts already inherent in agrifood production.

Redistribution: Distributing or donating food surplus to people in need. Fundamental to redistribution is that the food remains fit to consume, such that food safety risks in redistributed food should not differ from those of non-surplus food (FAO, 2022).

Valorization and conversion: Valorizing, or upcycling, creates opportunities to retain or add value in the reuse or recycling of food waste, either in the system or through conversion for use in other bio-based sectors. Examples include converting waste to animal feed or extracting a range of high-value substances, including food additives and antimicrobials, from food by-products such as peels, rinds and pomaces (Ueda *et al.*, 2022).

Nutrient or energy recovery: Recycling for nutrient or energy recovery has lower added value than the other three categories, although it still reduces the disposal of food waste in landfills. Recycling methods include anaerobic digestion of edible and inedible waste and the production of biogas, or applying the compost, vermicompost or digestates to land for soil conditioning and organic fertilizer.

A range of technologies and processes are used to convert food waste to value-added products or for nutrient and energy recovery. Bioactive compounds are extracted with solvents, ultrasound, subcritical water or enzymes, while processes such as composting, fermentation and anaerobic digestion enable nutrient and energy recovery (Kumar *et al.*, 2017; Roy *et al.*, 2023). However, the contaminant loading – microbial, chemical and physical – of food waste has the potential to persist through these recycling and valorization processes, and consequently presents a challenge for ensuring food safety. The reported occurrence of microbial, chemical and physical hazards in food waste and end-products from food waste recycling and valorization are compiled in the sections that follow. Moreover, as consumers increasingly consider environmental sustainability as a criterion for purchasing food products, steps to prevent fraudulent practices will need to be considered. Food fraud related to food waste can arise from adulteration using contaminated feedstocks or the provision of misleading information about the use of sustainable practices in the food value chain (Manning and Kowalska, 2021; Traynor *et al.*, 2024).

3.1 PATHOGEN AND CONTAMINANT OCCURRENCE IN FOOD WASTE AND FOOD BY-PRODUCTS

3.1.1 PATHOGENS

The occurrence of pathogens in food waste is contingent on the composition of the food types in the waste and the degree of spoilage and contamination before and after disposal as waste. A survey of food waste in both voluntary and regulated collection schemes from household and commercial sources reported the presence of foodborne pathogens including *L. monocytogenes*, *Salmonella* spp. and *Yersinia* spp. (Thakali *et al.*, 2022). However, a study of the microbial quality of food waste for potential valorization to animal feed found an absence of *Salmonella* spp. and generally low levels of other quality indicators (Tretola *et al.*, 2017). Similarly, *Salmonella* spp. and *L. monocytogenes* were absent, and staphylococcal enterotoxins, *Bacillus cereus* enterotoxins, Shiga toxin-producing *E. coli*, *Clostridium botulinum* and *Yersinia enterocolitica* were all below detection limits in a study of pelletized commercial and household food waste intended for animal feed (Castrica *et al.*, 2018). In biofertilizers derived from food waste, *B. cereus* concentrations ranged from 3.3 to 4.8 log cfu/g (Golovko *et al.*, 2022). Some bacterial species can be present in edible insects at specific stages of development when reared on organic waste (Box 6).

Correct maturation of food waste composts is usually sufficient to reduce pathogen loadings (Lemunier *et al.*, 2005), and many countries have statutory or voluntary standards for time and temperature requirements for compost sanitization (Hogg *et al.*, 2002). Vermicomposting food waste has variable efficacy in controlling pathogens. For example, survival of *E. coli* is variously reported as high or low through the process. This is likely contingent on antagonistic bacteria and chemical properties of the waste (Cao *et al.*, 2016; Hénault-Ethier, Martin and Gélinas, 2016).

The transmission of parasites could be a concern if food waste valorized for feed purposes contains infected tissue, such as encysted *Trichinella* spp. in wild or domestic pork (Boumans *et al.*, 2022). There is also increasing concern over the potential for transmission of allergenic peptides from food waste valorized to animal feed into resulting animal food products. A study of *Anisakis simplex*, a fish parasite, reported that its allergenic peptides could be transferred from feed into chicken meat, albeit with an unknown allergenic potency (Saelens *et al.*, 2023).

3.1.2 ANTIMICROBIAL RESISTANCE GENES

A review by Thakali and MacRae (2021) reported a range of studies identifying the presence of ARGs in food during production and processing, which suggests a possible occurrence of ARGs in food waste. There is contrasting evidence of the behaviour of ARGs in food waste treatment. Studies of food waste composting facilities in the United Kingdom of Great Britain and Northern Ireland and in China have found that finished products had appreciable levels of antimicrobial resistance (AMR) in the bacterial populations (Furukawa, Misawa and Moore, 2018; Liao *et al.*, 2019). In the China study, ARGs and mobile genetic elements (MGEs) persisted throughout the composting process, and even increased in abundance despite the initial bacterial host abundance and species diversity decreasing (Liao *et al.*, 2019). However, in a study of industrial-scale municipal solid waste composting, the abundance of ARGs increased in the thermophilic stage but decreased in the stabilization phase as the host bacteria were reduced, although MGEs hindered the reduction (Tang *et al.*, 2020). A study of pathogens in vermicomposting in South Africa found a pathogenic bacterium (*Salmonella enterica* serovar Typhimurium) in a single sample out of sixty and reported that this was resistant to kanamycin, but susceptible to other antimicrobials (Atanda *et al.*, 2018). The presence of ARGs in edible insects has also been attributed to feed based on food waste (Box 6).

3.1.3 PRIONS

The transfer of prions represents an area of potential concern where food waste or food by-products may be valorized into animal feed. This is because the level of treatment needed to denature these proteins may need to be greater than that used for pathogen deactivation (Chen, Jin and Shen, 2015). Screening of scrapie prion elimination by yeasts cultured on food waste used to produce animal feed found a reduction in levels of prion activity occurred, although potentially not to the degree where it could be the sole control (Huyben *et al.*, 2018). Composting for 28 days was reported to reduce levels of bovine spongiform encephalopathy prions in feedlot manures, particularly following the addition of feathers, which were hypothesized to enrich the compost for keratinolytic microorganisms (Xu *et al.*, 2022).

3.1.4 CHEMICAL CONTAMINANTS

Mycotoxin formation is a concern, particularly in food waste that is approaching the end of or is past its shelf life. A study of household food waste found that, in summer conditions, 75 percent of the samples were heavily contaminated with *Penicillium* spp., with corresponding contamination with mycotoxins, including mycophenolic acid, roquefortine and penitrem A (Rundberget, Skaar and Flåøyen, 2004). In the same study, food industry waste also had *Penicillium* spp. contamination, with 23 percent showing presence of mycophenolic acid. However, this contamination is not always present, as a separate study reported *Lactobacilli* as the predominant spoilage organisms in food waste and an absence of fungal pathogens or aflatoxin B1 (Wu *et al.*, 2018).

When food waste is valorized into food or feed uses, mycotoxin contamination transfer presents a concern for food safety. For example, aflatoxin contamination of dairy animal feed leads to aflatoxin M1 presence in milk (Iqbal *et al.*, 2015). A study of valorization of press cake, a by-product of plant beverage production, reported the presence of deoxynivalenol, which increased in some products with fermentation (Bartkiene *et al.*, 2020). Another study found that dried distillers' grain for use in animal feed contained enniatin B in all tested samples (Mortensen *et al.*, 2014). A wide review of mycotoxin occurrence in food by-products identified that aflatoxin B1, ochratoxin A, fumonisins, deoxynivalenol and zearalenone were all commonly present, with dried distillers' grain with solubles having the highest concentrations (Lopes *et al.*, 2023). For cacao shells, all samples were positive for aflatoxin B1 and ochratoxin A, while over 90 percent of grape pomace samples showed the presence of ochratoxin A but at much lower concentrations (Lopes *et al.*, 2023). In food by-products, such as dried distillers' grain, with a longer history of valorization to feed, the use of mycotoxin-degrading enzymes in food production has proven to be a promising mitigation strategy to reduce mycotoxins levels in the by-product (Focker *et al.*, 2021). Feeds contaminated with mycotoxins may also be treated with a range of binders, such as micronized fibres that can be derived from other food by-products, including apple and grape pomaces, artichoke wastes and almond hulls, to immobilize mycotoxins and prevent gastrointestinal absorption (Fumagalli *et al.*, 2021).

Persistent contaminants, such as metals, polychlorinated biphenyls (PCBs) and dioxins present a potential concern in certain food wastes, such as oilseeds and fish wastes (Taverne-Veldhuizen *et al.*, 2020; Focker *et al.*, 2022). Digestates from biogas production, which included food wastes, have been reported to contain a range of persistent organic contaminants, including dioxins, polybrominated diphenyl ethers (PBDEs), PAHs, naphthalene and PFAS, as well as the emerging contaminants di-2-ethylhexyl phthalate (DEHP), linear alkylbenzene sulfonate and nonylphenol (Suominen, Verta and Marttinen, 2014). Furthermore, biofertilizers from food waste digestates have been found to have an array of emerging contaminants, including high concentrations of plant alkaloids (nicotine, caffeine and theobromine), fungicides, parabens and pharmaceuticals (Golovko *et al.*, 2022). Household food waste composts have also been reported to have residual pesticide presence (Růžičková *et al.*, 2021), while a study of contaminants introduced at various food supply stages found that many heavy metals would exceed regulatory limits for composts, should waste be directed to this route (Thakali and MacRae, 2021).

Valorization of bio-actives from fruit peels and rind may present a pathway for surface-bound pesticide residue to concentrate (Nguyen *et al.*, 2020), while residual pomace, seeds and extracts also often concentrate residues (Rose, Lane and Jordan, 2009; Sójka *et al.*, 2015). Additionally, some inedible food wastes have been shown to accumulate certain metals, with aluminium being high in spent tea leaves (568 mg/kg dw), radish peels (470 mg/kg dw) and pineapple peels (590 mg/kg dw), and cadmium being high in olive pomace (2.9 mg/kg dw) (Kuppusamy, Venkateswarlu and Megharaj, 2017). Lastly, some components of produce concentrate more toxins, so that when collected in bulk, they present a concern. These include potato peels, which contain higher glycoalkaloid levels than tuber flesh. Therefore, valorization of potato peels for feed or into potato peel powder for food use can result in a higher exposure of consumers to potentially toxic substances such as glycoalkaloids (EFSA CONTAM Panel, 2020).

Circular processes for food waste may, however, result in products with low risk of chemical contaminants. In a study of pelletized food waste intended for animal feed, mycotoxins and pesticides were below detection levels, while the levels of lead, cadmium and arsenic complied with regulatory limits (Castrica *et al.*, 2018). Assessments of fish pellets derived from food waste have found that the food safety risks in aquaculture carp species from bioaccumulation of organochlorines and heavy metals were within acceptable ranges (Cheng *et al.*, 2014, 2016). Furthermore, there is evidence that the tissue accumulation of heavy metals in earthworms in vermicomposting reduces the presence of the contaminants in the end product (Soobhany, Mohee and Garg, 2015). There is potential for substituting existing products containing known but elevated concentrations of contaminants with a food waste-derived product having a more favourable contaminant profile (Man *et al.*, 2020). Both accumulation and reduction of chemical contaminants by edible insects raised on food waste has been reported for various species (Box 6).

3.1.5 PHYSICAL HAZARDS

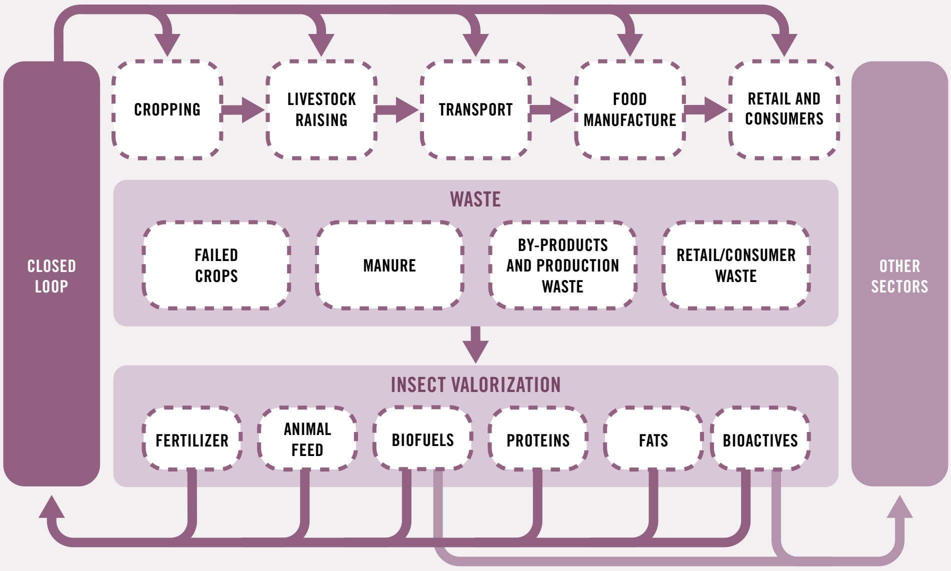
A further concern in food waste is the potential for co-occurrence of other wastes. Food waste can be contaminated with fibrous waste or plastic packaging if processes for separation or screening are inadequately applied (Thakali *et al.*, 2022). For example, if not removed from waste crop material, plant support twines will transfer into the composting process (FAO, 2021a). In addition to the physical hazards to handlers, these other wastes often introduce other contaminants, such as microplastics and plastic additives (FAO, 2021a). A study of compositing operations in China reported that leachate generated during food waste compositing had elevated cadmium. This is likely a result of plastics mixed into the feedstock (Chu *et al.*, 2019). The presence of macro- (>25 mm), meso- (5–25mm) and microplastics (1–5000 µm) in compost was estimated to result in a yearly agricultural soil loading of 10^4–10^5 g/ha of macro- and mesoplastics and 10^7–10^8 items/ha of microplastics (Scopetani *et al.*, 2022). Additionally, this loading was also linked to the elevation of the plastic additive contaminants DEHP, acetyl tributyl citrate, nonanal and dodecane in agricultural soils (Scopetani *et al.*, 2022). As has been noted, the food safety risks from microplastics are not fully understood. However, the associated elevation in plastic additives in the compost potentially presents a pathway for uptake of these contaminants into food crops.

BOX 6

VALORIZATION OF FOOD WASTE THROUGH INSECT REARING

Raising insect species, such as black soldier fly larvae (*Hermetia illucens*), crickets, house flies (*Musca domestica* L.), locusts and mealworms (*Tenebrio molitor*) on food waste and food by-product waste is increasingly being explored as an option for valorizing food waste (Skrivervik, 2020; Elleby *et al.*, 2021; Ojha, Bußler and Schlüter, 2020). Insects can feed on a range of food and other organic wastes, including manure, providing high-efficiency bioconversion with a favourable environmental footprint (Oonincx *et al.*, 2010; Fitches *et al.*, 2019) (See Figure 4).

FIGURE 4. **CIRCULAR AGRIFOOD PROCESSES FROM REARING INSECTS ON FOOD WASTE**



It is customary to consume insects as food in many countries, and even where it is not customary, using insects as food has been gaining regulatory approval as being safe (FSANZ, 2020; EFSA NDA Panel, 2021; FAO, 2021b). General food safety aspects related to consuming insects have previously been explored by FAO (2021b), concluding that, with the growth of the sector, there is a need for a thorough assessment of the associated food safety hazards.

Using insects directly as livestock feed may also occur, although in some countries, including European Union member states, feed derived from insects is captured under the definition of animal protein and, consequently, cannot be fed to ruminants (EC, 2021). Aside from the direct consumption of insects for food or feed, protein and oils extracted from insects are alternative sources to supplement and replace oilseeds and fishmeal production, reducing land and stock demands. Additionally, insects offer the potential to be processed to produce fertilizers, biofuels and bio-active compounds, with the frass by-product also being a source of fertilizer (Beesigamukama, 2020; Ojha, Bußler and Schlüter, 2020).

BOX 6 (cont.)

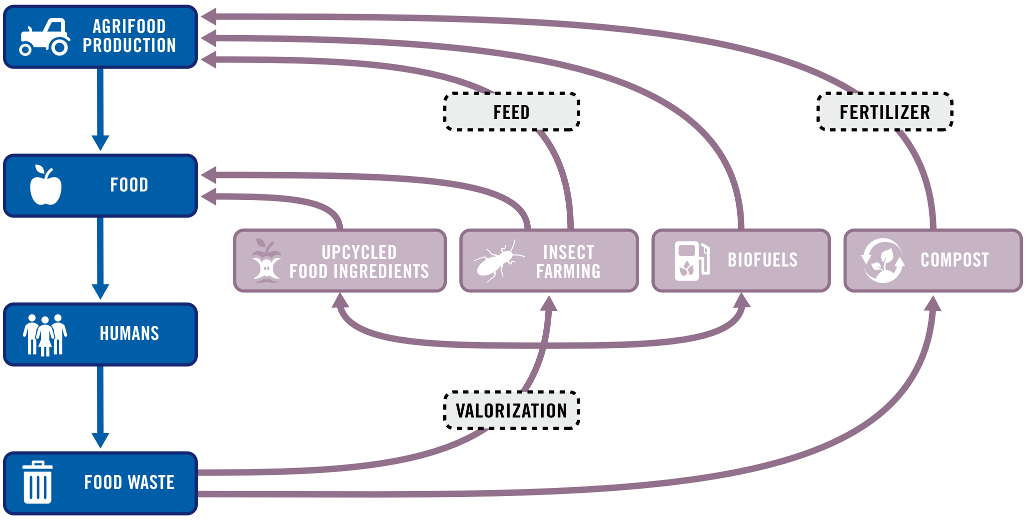
VALORIZATION OF FOOD WASTE THROUGH INSECT REARING

In relation to managing food waste, while there are problems with using contaminated food for animal feed, there are opportunities to rear insects on heavily mycotoxin-contaminated crops that would not be acceptable for food or feed (Evans and Shao, 2022). There is some evidence showing that while insects thrive on contaminated feed, they do not accumulate the toxins (Guo *et al.*, 2014; Camenzuli *et al.*, 2018). It should be noted, however, that the understanding of detoxification pathways in insects is incomplete, and there is potential risk for masked mycotoxins or toxic metabolites to be present in edible insects. Furthermore, insects may still accumulate other toxicants such as heavy metals (cadmium, lead and zinc), pharmaceuticals and mineral oils from food waste (van der Fels-Klerx *et al.*, 2020; Lievens *et al.*, 2021). For instance, black solider fly larvae were found to accumulate the pesticides boscalid, fluopyram and etofenprox from the raising substrate (Jensen *et al.*, 2022). Food waste contaminated with plastic packaging also presents some concerns as to potential transfer of additives, contaminants, and micro- and nanoplastics to the insect species (Beale *et al.*, 2022). An area that is increasingly being explored is raising insects on plastic waste substrates, given their potential to metabolize polymers such as polystyrene (Yang *et al.*, 2018) with no or little difference in the resulting nutritional profile from other growth media (Zielińska *et al.*, 2021). Mealworm larvae fed polystyrene containing the flame retardant hexabromocyclododecane (HBCD) were reported to have little to no bioaccumulation, passing the HBCD into the frass (Malawi Brandon *et al.*, 2018). However, the behaviour of other additives or contaminants, and consequently, potential risks of their retention in food or feed products, has not been widely studied to date.

Raising insects on organic waste streams also presents a potential risk arising from pathogens. Mealworm larvae appear to be poor hosts for *E. coli* and *Staphylococcus aureus*, with no growth or, for the latter, toxin production, evident following consumption of spiked feed (Cesaro *et al.*, 2022a, 2022b). However, *Salmonella* spp. and *Bacillus cereus* have been detected in black soldier fly larvae and their environments after rearing, suggesting microbial food safety must be taken into account (Wynants *et al.*, 2019). Insects prepared for human food (mealworms and crickets) have also been reported to contain transferable antibiotic resistance genes (ARGs), with notable differences between the two species, suggesting these could transfer from a food waste feed source (Vandeweyer *et al.*, 2019).

Sources: See References.

FIGURE 5. **LINEAR AND CIRCULAR MODELS OF FOOD WASTE AND BYPRODUCTS IN AGRIFOOD PRODUCTION**



Notes: **Blue** boxes and lines reflect the existing linear processes. **Purple** boxes and lines represent circular processes with some examples of valorization provided. **Grey** boxes detail the processes and applications in use.

CHAPTER 4

FOOD PACKAGING WASTE

Managing food packaging must focus on both eliminating the production of avoidable or unnecessary waste and managing the legacy of the packaging currently in circulation (UNEP, 2023). Plastic food packaging waste is a notable concern and three market shifts have been identified that are contributing to transform this sector to circularity: shifting from throwaway to reusable packaging products, accelerating plastic recycling, and redesigning and reorienting to develop safe and sustainable alternatives (UNEP, 2023). Other food packaging materials have adopted various degrees of circularity in their production, depending on the ease of segregating them from waste streams and on the technological capability to reuse or recycle the materials. When transforming food packaging and other food-related waste materials in the agrifood system to a circular approach, it is necessary to consider the food safety risks of moving away from virgin and single-use materials. The next sections discuss the three market shifts in light of research on food safety risks.

4.1 ACCELERATING PLASTIC RECYCLING

In many countries, recycling systems for some food packaging materials are already well-established. Metal containers, for instance those made from tinplate, steel and aluminium, are recycled at very high rates in many countries, with recycled material making up a high proportion of the total metal in use (Graedel *et al.*, 2011; Warrings and Fellner, 2019). Similarly, large-scale closed-loop recycling of glass means that recycled glass makes up a notable proportion of the glass in use in some countries, with the benefit of reduced energy use compared with glass production from virgin material (Zero Waste Europe, 2022). However, the recycling process for these materials is reported to occasionally cause emerging health risks. For instance, substandard forging processes for recycled aluminium cookware have led to high levels of leachable lead (Mathee and Street, 2020).

Recycling of paper and cardboard, both from within and outside the agrifood system, is also commonplace in many countries as these wastes are generally easily separated from other waste, either by consumers or in the waste collection system. Paper and cardboard waste is easily broken down and the cellulose fibres are reformed into new products, including food packaging (although not indefinitely, as fibre quality decreases with subsequent recycling) (Hubbe, Venditti and Rojas, 2007).

As chemicals are used in manufacturing paper and cardboard, the recycled products often contain a broad range of contaminants (Pivnenko, Eriksson and Astrup, 2015). Several studies have shown that contact between food and recycled paper and cardboard has the potential to result in the migration of a range of substances, including plasticizers, alkyl phenols, mineral oils and printing inks, into stored foods, albeit at levels typically not considered a health risk (Ozaki *et al.*, 2006; Triantafyllou, Akrida-Demertzi and Demertzis, 2007; Gärtner *et al.*, 2009; Suciu *et al.*, 2013). However, these represent only a limited selection of the potential contaminants, and there are challenges in standardizing testing methodologies to quantify the risk and conduct risk assessments on many of the potential contaminants in recycled paper and cardboard materials used in contact with food (Kourkopoulos, Sijm and Vrolijk, 2022). Aside from direct recycling, fibre-based packaging is often intended for recovery in composting streams. In line with the forementioned considerations for recycling organic wastes, this presents a risk for contaminants to persist in composts and enter agricultural soils.

Recycling is seen as key to improving the circularity of food-related plastics. Plastic recycling methods include reprocessing offcuts or scraps from virgin materials, physical reprocessing of post-consumer products (for instance, by grinding into flakes, melting and extruding) or chemical reprocessing (including depolymerization, purification and manufacturing new polymers) (Hopewell, Dvorak and Kosior, 2009). For post-consumer products, physical reprocessing often presents a concern arising from chemicals, such as plastic additives and contaminants from prior use, when these are retained from the feedstock and persist in the recycled material. Commercial plastic compositions include a range of additives, such as plasticisers, UV stabilisers or flame retardants, as well as contaminants, including catalysts and residual monomers. A mapping of published information on additives in plastics identified over 6000 substances in use, many of which had minimal toxicity information and a notable proportion of which were matched to regulatory agency priority substance lists (Aurisano, Weber and Fantke, 2021). Consequently, recycled plastics commonly contain a broad range of non-intentionally added substances (NIAS) that present potential contamination risks for food packaging and can be challenging to identify and evaluate (Kato and Conte-Junior, 2021). Samples of recycled high-density polyethylene (HDPE) and low-density polyethylene (LDPE) pellets reported 134 volatile and semivolatile organic substances, including surfactants and antioxidants as well as odours from decayed food (Horodytska, Cabanes and Fullana, 2020). In Canada, there was a high reported prevalence of organophosphate esters in use as plasticizers, stabilisers and flame retardants across recycled pellets and flakes for various recycled plastic types (Chibwe *et al.*, 2023).

Contamination is a particular concern where the plastics to be recycled originate from non-food uses, such as electronic waste or chemical storage containers. Non-food plastics frequently contain additives not intended for food contact that are retained in the recycled use. Plastics used for non-food storage may absorb chemicals, resulting in the risk that these will migrate into a recycled food-contact use. A study of recycled HDPE pellets from across 23 countries reported the occurrence of polybrominated diphenyl ethers and benzotriazole UV stabilizers, with the source believed to be from recycling electronic waste due to poor source-material segregation (Brosché, *et al.*, 2021). Recycled polyethylene terephthalate (PET) bottles have been reported to contain undesired substances from prior non-food uses, including ethanol and ethylene glycol, and flavourings such as anethole and limonene (Franz and Welle, 2020).

Reclaimed ocean and ocean-bound plastics are being used as a feedstock for mechanical and chemical reprocessing into recycled food and non-food packaging (Romeo, 2017; FSA COT, 2022). A review in the United Kingdom of Great Britain and Northern Ireland established that marine and riverine plastics regularly contain a range of contaminants, including PAHs, PBDEs and PCBs (FSA COT, 2022). Further, marine plastics are known sinks for emerging contaminants, such as the phenolic benzotriazole UV absorber UV-328, a Stockholm Convention-listed persistent organic pollutant (UNEP, 2022). This presents a potential concern over the fate of these contaminants during recycling and the levels retained in any food packaging materials.

Maintaining packaging integrity is a key criterion to retain a barrier to microbial and chemical contamination of food from the environment and limiting food waste spoilage. Therefore, degrading packaging presents a concern for contamination of stored food from migrating substances and physical fragments from the packaging. There are limits to the recyclability of certain materials, with, for example, polypropylene showing degradation through reprocessing (Eriksen *et al.*, 2019). Consequently, it is important that product design and material sorting ensure recycled packaging retains its integrity.

Functional barriers may be used to limit the migration of any NIAS or other contaminant from recycled materials into stored food (Welle, 2023). Barriers include laminating or co-extrusion of a virgin layer of the same polymer, coating with a barrier lacquer, or use of multiple material layers (Welle, 2023). The use of multiple polymers or the introduction of a lacquer substance, however, makes the resulting packaging heterogeneous and difficult to further recycle, increasing the likelihood that these materials are then lost as landfill waste (Soares *et al.*, 2022).

4.2 SHIFTING FROM THROWAWAY TO REUSABLE PACKAGING PRODUCTS

The reuse of food packaging or containers offers the ability to extend the life cycle of single-use items. The agrifood system can support reuse through the design of an end-of-use collection system or by segregating these items from waste. Additional measures include influencing or incentivizing consumers to purchase and utilize reusable containers (Nicolau *et al.*, 2022).

Successful reuse relies on avoiding cross-contamination between uses and ensuring that the product retains integrity, and that any deterioration does not pose a risk to food safety. Avoiding cross-contamination is a notable challenge, as successfully cleaning packaging to remove the variety of foodstuffs it may contain and validating the cleanliness requires optimized processes (Nahar *et al.*, 2023). However, cleaning is critical for food safety, as many pathogens are reported to survive for days or even weeks on a variety of materials used in reusable packaging, including glass, aluminium and plastic (Wißmann *et al.*, 2021). Polypropylene used in reusable produce crates was reported to have a higher risk of *Salmonella* spp. cross-contamination to cauliflower than single-use materials (López-Gálvez *et al.*, 2021). Inadequate cleaning between uses may also increase the contamination risk. A study in Ghana recorded higher faecal coliform counts in washed PET water bottles than in unwashed bottles (Abrokwah, Ekuman and Abrokwah, 2020). Cleaning is also necessary to remove any allergens from prior use.

Decontamination of any chemical contaminants, for instance through multiple water or detergent rinses, is also important before reuse, particularly where packaging or containers were previously used to store non-food materials. For example, misuse of refillable PET bottles (used to store alcohol, cleaning products and fuels) was identified as a potential source for organoleptic impacts identified by consumers in mineral water and soft drinks (Widén, Leufvén and Nielsen, 2005). Of greater concern is that unsafe storage of hazardous chemicals in reusable or refillable containers could lead to toxicity if not decontaminated. A study of decontamination of containers for agrochemicals found triple-rinsing ineffective for full decontamination of some pesticide residues, meaning the container still needed to be treated as hazardous (Picuno *et al.*, 2020).

Degradation is a concern with the long-term reuse of packaging if it facilitates the migration of any additives or contaminants to the container or the release of physical fragments, such as microplastics. Microplastic levels in water from reusable plastic bottles were an average of 118 particles/l, compared to 14 particles/l in single-use plastic bottles (Schymanski *et al.*, 2018). Subjecting reusable packaging to cooking presents specific issues. For example, repeated hot-filling or microwaving was associated with the release of silver and silver- and silicone-containing microplastics from reusable packaging with antimicrobial properties (Moreno-Gordaliza, Marazuela and Gómez-Gómez, 2023). It is also important to note that cleaning processes can accelerate any degradation. A study of polyethylene bottles reused for one year indicated that a range of different substances, including plasticisers, antioxidants and photoinitiators, had migrated into stored water, with migration rates being enhanced following dishwashing (Tisler and Christensen, 2022).

Technical guidance has been developed to support the reuse of plastic crates as bulk packaging for fresh produce (FAO, 2009). Recommended practices to manage microbial, chemical and physical hazards include:

> discarding damaged containers when they start to degrade or are difficult to clean;

> marking containers in contact with soils, composts or faecal material to prevent them from being reused;

> cleaning and sanitizing containers, using both physical and chemical methods, before being used to transport fresh produce; and

> avoiding the use of containers that have been used to transport contaminating cargoes, such as pesticides or tools.

4.3 REDESIGNING AND REORIENTING PACKAGING TO DEVELOP SAFE AND SUSTAINABLE ALTERNATIVES

Innovation and redesign focus on opportunities to reduce the generation of packaging waste, for example by reducing the volume of non-renewable materials, replacing them with renewable and biodegradable materials, and increasing the longevity of packaging and its functionality for reuse. A challenge in the redesign of food packaging to biodegradable or biopolymers has been ensuring high barrier properties to oxygen and water, as well as integrity to other stresses in use and storage (Zhong *et al.*, 2020; Wu, Misra and Mohanty, 2021). The inability to maintain integrity presents a risk of entry of spoilage organisms and, hence, of reduced shelf life and greater food wastage. However, research strategies, such as the design of nanocomposite materials, are underway that aim to achieve comparable integrity to current non-biodegradable materials (Wu, Misra and Mohanty, 2021; Versino *et al.*, 2023).

Development of edible packaging offers the potential to reduce packaging waste and valorize food waste streams (Hamed, Jakobsen and Lerfall, 2022). For example, pectin from processed citrus peel and apple pomace has applications in the design of edible films, while kitchen food waste is a possible medium to produce the packaging thickener pullulan through culturing *Aureobasidium pullulans* (Rishi *et al.*, 2020; Ajesh Kumar *et al.*, 2022). However, chemical and microbiological hazards from food waste sources present challenges. Additionally, the derived material must be safe to consume and act as a suitable barrier to protect the incorporated food

People shopping at a supermarket in Tajikistan.

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product. The design of edible packaging must account for any additive uses and the potential for allergens in its composition to be acceptable to consume.

The transformation of packaging design to biopolymers is an area of interest to improve the waste problem posed by hydrocarbon-based polymers (Zhu *et al.*, 2022). As with edible packaging, biopolymers used, or with the potential to be used, in food packaging, such as cellulose nanofibers, chitinous composites and lignocellulosic composites, can source feedstock from the valorization of food waste (Abdul Khalil *et al.*, 2016; Jones *et al.*, 2019, Elsacker *et al.*, 2020). Bio-based polymers, such as polylactic acid, can be produced through the microbial fermentation of food waste biomass (Bonwick *et al.*, 2019).

Food-waste-sourced polymers may be subject to contaminant loading from food waste and there is potential for these to migrate into food packaging (Bonwick *et al.*, 2019). These contaminants can include myco- and phytotoxins, persistent organic contaminants, heavy metals and process contaminants such as acrylamide that are formed in cooked foods (Bonwick *et al.*, 2019). Allergenic proteins could also persist in the biopolymer from the source food-waste feedstock. It is therefore important that the production process confirms the level of removal or denaturing of such allergenic proteins in order to avoid the risk of cross-contaminating food when biopolymers are used in packaging (Bonwick *et al.*, 2019).

Biodegradable materials, whether fibre-based or biopolymers, are commonly used in the redesign of packaging to support disposal through composting systems, and consequently divert the waste from landfill (Raźniewska, 2022). As with the

Workers packing yellowfin tuna in Maldives.

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considerations for recycling organic wastes, there is a potential for contaminants in packaging to persist in composts and enter agricultural soils. A further concern is that, without raising awareness of which materials are compostable, non-biodegradable or contaminated, they may incorrectly be disposed of and contribute to chemical and physical fragment contamination of the end-use compost (Raźniewska, 2022).

Redesign of food packaging to improve environmental sustainability should be carefully implemented so as not to erode food safety or increase opportunities for fraudulent practices. A prominent example is the introduction of food contact materials, including reusable cups, containing bamboo fibre, ground bamboo and bamboo flour (Bouma, Kalsbeek-van Wijk and Sijm, 2022). Using a biodegradable component, these food contact materials were promoted as more environmentally sustainable, although the material was commonly mixed with a melamine resin. A consequence was that certain items had a high level of melamine and formaldehyde migration into food products, necessitating recalls in many countries (EC, 2022). The redesign of packaging to use alternative materials can also result in the use of components with limited toxicity information to inform risk assessment in the case of migration. For example, the substitution of bisphenol A has resulted in the use of a range of alternatives with limited or absent toxicity data, which hampers the assessment of dietary exposure (den Braver-Sewradj, van Spronsen and Hessel, 2020). Redesign to reduce packaging materials for retailed foods should not compromise the readability of label content to inform consumers of the nutritional information and any health considerations in the food, such as allergens or shelf life. Conversely, however, labelling often necessitates the use of inks, photoinitiators and adhesives, which may be retained in the recycled material, reducing its material value and representing a potential risk of migration into food (Aparicio and Elizalde, 2015; Gabriel and Maulana, 2018). Improving the circularity of packaging is also contingent on regulatory authorities managing labelling requirements that are commensurate with the necessary risk and essential nutritional information.

As noted above, packaging plays an important role in managing food waste. There are opportunities for innovation in packaging focusing on improving shelf life (Box 7), reducing loss of food during storage and transport, minimizing contamination and helping retailers and consumers better identify spoilage. A difficulty in innovation for food waste reduction is whether this “improved” packaging is detrimental to the circularity of food packaging. For example, multilayer packaging has several emerging food applications to increase the longevity of food and provide a barrier to the migration of NIAS for recycled layers (Aparicio and Elizalde, 2015, Anukiruthika *et al.*, 2020). However, at present, multilayer materials are difficult to recycle, with few options to retain the value of this product (Soares *et al.*, 2022). Using labelling to improve awareness on food waste and reduce any confusion over the shelf life of food for quality vs safety reasons, is regarded as playing a significant role in limiting food waste, but also in increasing the circularity of the packaging (Williams *et al.*, 2020; FAO, 2022b; Patra, Feng and Howard, 2022). A net benefit approach could be justified for adding packaging material, such as incorporating measures or seals, or packaging smaller quantities of food, if this decreases the amount of food waste generated by supporting consumers to better use or store food (Williams *et al.*, 2020).

BOX 7

ACTIVE AND INTELLIGENT PACKAGING

Incorporating technological advances into food packaging is an area currently undergoing development. Active packaging involves incorporating chemical substances to improve shelf life and reduce the risk of microbial spoilage and safety issues, while intelligent packaging involves the use of sensors to track the quality and degradation of packaged food in real-time to provide information about its storage conditions, freshness and possible spoilage (Soltani Firouz, Mohi-Alden and Omid, 2021).

There is high interest in active and intelligent packaging for potentially improving shelf life and providing protection from contamination. Coupling these technologies with the use of biodegradable components provides potential benefits in reducing both food waste and food packaging waste (Bhargava *et al.*, 2020). The circularity of this concept can be further increased by valorizing food waste as feedstock in active packaging (Zainal Arifin *et al.*, 2023), albeit with the risk of contaminants retained from the feedstock migrating into stored food.

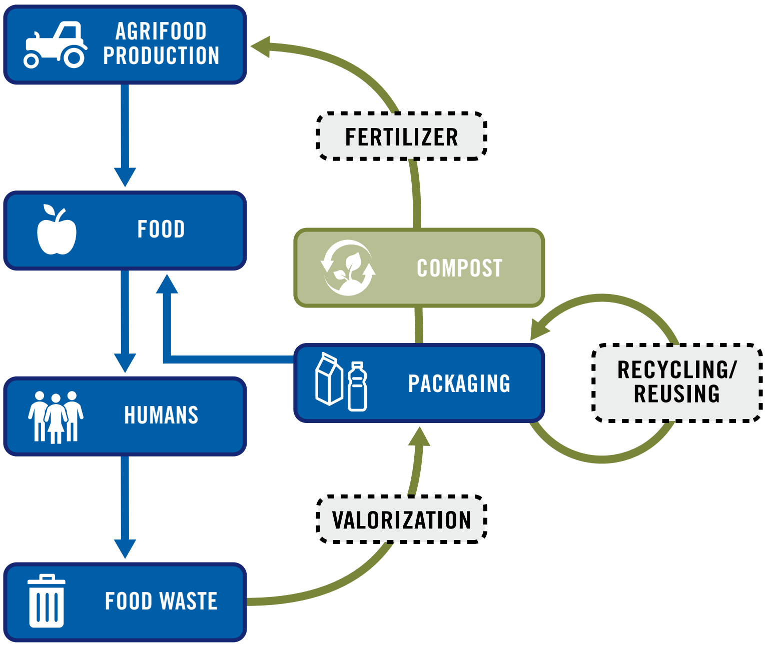
A broad review identified applications of a variety of natural products in active packaging. These natural products include natamycin, garlic extract, plant essential oils, chitosan and methylcellulose, which have an inhibitory effect on fungal spoilage across various foods, resulting in limited mycotoxin contamination (Jafarzadeh *et al.*, 2022). Furthermore, metal nanoparticles, for example silver or titanium dioxide, can serve an antimicrobial and antifungal role in active packaging (Bonwick *et al.*, 2019; Ahari *et al.*, 2021). A range of bio-based dyes are being explored for their potential use in intelligent packaging designs. Pigments such as anthocyanins, curcumin, chlorophyll and carotenoids, as well as inorganic molecules, such as copper acetate and silver nanoparticles, are being analyzed for colorimetric sensing of changes to pH or generation of spoilage molecules, such as hydrogen sulphide or biogenic amines (Halonen *et al.*, 2020).

The benefits of active and intelligent packaging in limiting food waste or microbial contamination must be weighed against the risk of the potential migration of the active substances used for this purpose into the food. For example, intelligent packaging sensors, such as dyes in time temperature indicators, could cause a potential risk if they migrate or leak into the stored food product (Bhargava *et al.*, 2020; Luo, Zaitoon and Lim, 2022).

Despite the benefits offered by such advanced packaging materials to reduce food loss and waste, there are issues around environmental sustainability stemming from the lack of appropriate recycling or other end-of-use streams dedicated to these materials. For example, a paper coated with polylactic acid containing zinc oxide nanoparticles was reported to have a transfer of 7 to 16 percent of the nanoparticle into the accepted material stream, indicating it is retained as a non-intentionally added substance (NIAS) in the recycled material (Zhang *et al.*, 2016).

Sources: See References.

FIGURE 6. **LINEAR AND CIRCULAR MODELS OF FOOD PACKAGING WASTE IN AGRIFOOD PRODUCTION**



Notes: **Blue** boxes and lines reflect the existing linear processes. **Moss green** boxes and lines represent circular processes. **Grey** boxes detail the processes in use.

Rice-fish farming in the Lao People's Democratic Republic.

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CHAPTER 5

INTEGRATED FARMING SYSTEMS

Traditional circular practices, such as intercropping and crop rotation, are retained in modern agrifood systems due to their ability to cost-effectively retain soil nutrients and reduce disease and pest pressures (Schneider *et al.*, 2021). Integrated farming builds on these approaches to greater synergize different streams of agricultural production in order to improve land use efficiency and beneficially recycle wastes within the system.

An established example used across Asia is integrated rice–duck farming (IRDF), where ducks are raised in rice paddies and control pests and weeds through foraging, reducing the need for agricultural chemicals (Box 8). In addition, their droppings provide nutrient inputs for the plants (Suh, 2014). Other species are often integrated, forming complex rice systems (FAO, 2022c). For example, *Azolla*, an aquatic fern, provides nitrogen fixation, feed for the ducks and suppression of aquatic weeds. Fish species, such as tilapia, are also raised in the rice paddies to provide aquatic pest control and inputs of additional nutrients through their droppings (Sapcota and Begum, 2022). Aside from recycling waste in the system, this reduces the need for agricultural inputs and adds potential gains in productivity (Yuan *et al.*, 2022).

Other integrated models include aquaponics, which, as outlined in the section covering water scarcity, combines hydroponics and fish-raising systems. In addition to reducing the waste of water resources, aquaponics ensure nutrient-rich fish droppings are recycled for plant growth (Goddek *et al.*, 2015). Another integrated model is grazing livestock in permanent orchards, vineyards, forestry sites or even urban parklands (Davis, 2021; Paut *et al.*, 2021). A study in India found that a system integrating vegetable and arable cultivation with mushroom production, beekeeping and vermicomposting had high levels of nutrient recycling as well as high productivity and profitability (Shyam *et al.*, 2023).

Lastly, there are initiatives underway to integrate bioenergy production into agriculture through anaerobic digestion of manures and crop residues (McCabe *et al.*, 2020). Aside from their recovery for energy, the resulting digestates can be recycled on the farm, leading to reported benefits in reducing GHG emissions, reducing the need for mineral fertilizers, and improving soil health through using land for biomass crops instead of fallow (McCabe *et al.*, 2020).

5.1 PATHOGEN OCCURRENCE IN INTEGRATED FARMING

Many integrated systems rely on manure or droppings as a source of nutrients. This entails a risk of pathogen persistence in edible foods. A study of an aquaponics system confirmed that Shiga toxin-producing *E. coli* was present in the recirculating water and could contaminate root surfaces of vegetables, although it was not reported to internalize into the leaves of fruits (Wang, Deering and Kim, 2020). *Salmonella* spp. and *L. monocytogenes* were, however, not detected in the fish faeces, water or vegetables. However, an advantage of controlled-environment agriculture systems, such as aquaponics, is that controls can be introduced and maintained to prevent pathogen, pest and disease entry to the system (Desponina, Avgoustaki and Xydis, 2020). Direct contact between manure and produce, for instance when animals are grazing in orchards, also presents a pathogen risk, particularly if the produce is intended to be consumed raw. A further consideration when multiple animal species occupy the same land area is the potential for the completion of life cycles of parasitic species, which will transmit to humans via food products. For example, fish are the second intermediate host and poultry are a paratenic host for *Gnathostoma* spp. Integrated systems raising both species may increase the risk of foodborne transmission from raw or undercooked tissue of these species, particularly if definitive hosts, such as cats, dogs and pigs, are also present (Liu *et al.*, 2020). Similarly, integrating the production of livestock and rice or other aquatic plants increases the risk factors for the parasite *Fasciola*, as parasite eggs could enter the aquatic environment from manure, while the metacercariae are known to encyst in rice fodder and straw (Gray, Copland and Copeman, 2008). Further integration of ducks, however, is a possible control strategy through predation of snails, the intermediate host, and through biological control as a natural reservoir for competing *Echinostoma* flukes (Gray, Copland and Copeman, 2008).

5.2 CHEMICAL OCCURRENCE IN INTEGRATED FARMING

It is necessary to understand the life cycle of different inputs, such as agricultural chemicals and veterinary medicines, within the different system modules of an integrated model. Some veterinary medicines have the potential to be taken up from soil into crops. For example, trimethoprim was reported to transfer to lettuce and carrot roots (Boxall *et al.*, 2006). When animals graze in orchards or vineyards for weed control or leaf plucking there is a risk that soil concentrations of legacy pesticides, such as organochlorines, can bioaccumulate in edible tissues of grazing animals (Sadler *et al.*, 2005; Conrad *et al.*, 2022). Further grazing in unconventional areas may lead to livestock exposure to other contaminant sources, such as poisonous plant species, the residues or contaminants of which could transfer to meat and milk (Panter and James, 1990; López, Cid and Bianchini, 1999).

In many cases however, changing the production system has a limited impact on the presence of chemical contaminants in food when compared to conventional production systems. For instance, a study of a rice–duck–crayfish integrated system reported no notable variation in heavy metal concentrations and bioavailability compared to conventional cultivation systems (Yan *et al.*, 2023). Furthermore, because of the introduction of natural pest and disease controls, integrated farming practices can result in reduced agrochemical use and, potentially, a decreased residue profile in the food produced (van der Werf and Bianchi, 2022).

BOX 8

INTEGRATED RICE–DUCK FARMING SYSTEM

Polyculture of free-grazing ducks in rice paddies has been a long-standing traditional practice in parts of Asia that is seeing increased interest as a low-cost solution to improving agricultural circularity and adapting to a changing climate (FAO, 2013; Zhang *et al.*, 2023). The integrated rice–duck farming (IRDF) system takes advantage of a synergy in agricultural practices through co-production of distinct food commodities like rice, duck meat and eggs on the same farmland. Ducks acting as natural predators of plant pests and also contributing nutrients to the paddy soils through manure have shown potential benefits in reducing the need for pesticides and fertilizers, as well as improved soil fertility, biodiversity and increased crop yields and nutritional quality (Long *et al.*, 2013; Teng *et al.*, 2013).

Integrating the two species in a farming system, however, can present a pathway for the transfer of zoonotic pathogens. A review of rice production in Cambodia identified waterfowl, including domesticated ducks, as reservoirs for a range of zoonotic diseases including those such as salmonellosis, and escherichiosis with possible food safety implications (Sievers *et al.*, 2024). Ducks raised in these situations may be at greater infection risk due to the paddies also being habited by wild birds and other disease vector species. A study of ducks in integrated duck–rice farms in Thailand reported a high level of seropositivity to *Toxoplasma gondii*, hypothesized to be from ongoing peroral transmission of waterborne pathogens in the raising environment (Nguyen *et al.*, 2023). Similarly, echinostome infections in free-grazing ducks were high, suspected to be from the occurrence of intermediate hosts in the paddies (Saijuntha, Duenngai and Tantrawatpan, 2013). The consumption of undercooked duck meat could present a foodborne transmission pathway where parasite levels or parasitic cysts are high.

Although chemical inputs may be lower in IRDF systems, those chemicals that are used for pest or disease control present a risk of transfer between the two species. For example, a range of agricultural chemicals are reported to be used in rice cultivation and the presence of highly persistent and/or toxic organochlorine and organophosphate insecticides are a particular concern over potential to transfer to duck tissues (Khammanee *et al.*, 2020). Veterinary treatments for the ducks may enter the paddy water or contact the crop when excreted and present a risk of crop uptake. For example, a low level of uptake and translocation to rice grains from irrigation water was reported for the veterinary antibiotics amoxicillin, chlortetracycline and oxytetracycline (Duong *et al.*, 2023). With the incorporation of additional species, progressing to complex rice systems, there is a potential risk that further chemical inputs are introduced, for example aquaculture antibiotics for managing fish or crayfish diseases.

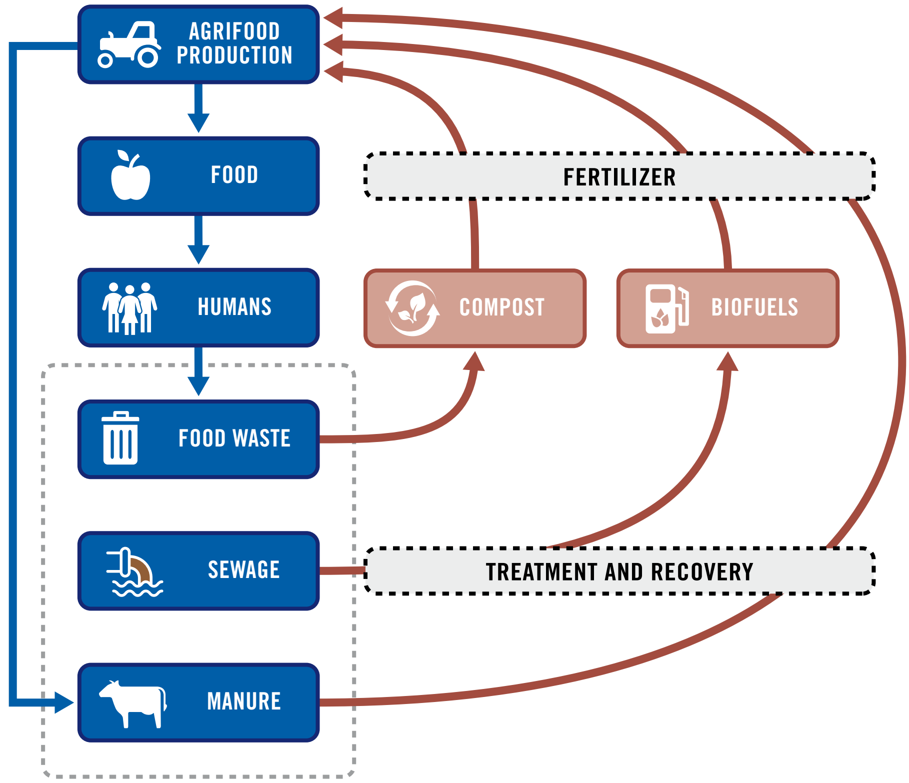
BOX 8

INTEGRATED RICE–DUCK FARMING SYSTEM (cont.)

The inputs of antibiotics whether intentional or indirect through manure, as well as high and diverse microbial loadings in the production environment present a risk of generation and transfer of antibiotic resistance genes (ARGs). Livestock manure, including poultry, inputs into aquaculture systems has been reported as a risk factor for development of antimicrobial resistance (AMR) (Dewi *et al.*, 2022; Petersen *et al.*, 2002; Watts *et al.*, 2017) providing a concern these conditions are comparable for IRFD systems.

Sources: See References.

FIGURE 7. **LINEAR AND CIRCULAR MODELS IN INTEGRATED FARMING SYSTEMS**



Notes: **Blue** boxes and lines reflect the existing linear processes. **Red** boxes and lines represent circular processes. **Grey** boxes detail the processes in use.

CHAPTER 6

INTERCONNECTEDNESS OF CIRCULAR SYSTEMS AND FOOD SAFETY CONSIDERATIONS

In the previous chapters, there is a common thread describing processes by which different categories of waste or by-products can be recovered, reused, valorized or recycled. In practice, each of these processes is unlikely to function in isolation, especially as the transformation of agrifood systems to circularity aspires for more interconnected flows of materials through multiple interlocking processes. Examples include food waste valorization to produce food packaging which can then be composted as a nutrient input to soil, or food waste used to raise insects for feed production (Koppelmäki, Helenius and Schulte, 2021). In addition, there is a focus on expanding the scope of applying circular principles at both the national and international levels. Implementing appropriate food safety management measures can help to reduce the occurrence of microbial contaminants in resources coming out of a material process and entering another. For example, introducing a heat treatment step will considerably reduce the potential risk of pathogens present in desired food waste resources entering into packaging production processes. However, the interconnectedness of circular processes within agrifood systems can present challenges for contaminants, particularly chemicals, that can persist and accumulate in such processes (Focker *et al.*, 2022). Per- and polyfluoroalkyl substances (PFAS) are pervasive as persistent contaminants in wastes, hence are highlighted as a specific concern for interconnected circular agrifood systems (Box 9).

BOX 9

PER- AND POLYFLUOROALKYL SUBSTANCES – THE CONTAMINANT OF CONCERN FOR THE CIRCULAR ECONOMY

Research over the last 20 years has established that per- and polyfluoroalkyl substances (PFAS) are ubiquitous global environmental contaminants. A range of PFAS congeners have and continue to be used in societal and industrial applications (OECD, 2013). Many forms of PFAS will undergo transformation in the environment, progressing to end products that are highly resistant to environmental degradation (OECD, 2013). PFAS show differing environmental fate and transport properties, commonly based on chain length and functional groups (Tang *et al.*, 2022). For example, polyfluoroalkyl phosphate diesters (diPAPs) are of low mobility in soil but form leachable perfluorocarboxylic acids as they degrade (Lämmer *et al.*, 2022). This variety of chemical properties and the ability of environmental PFAS to partition and concentrate into different waste materials make them a contaminant of particular concern in circular agrifood systems, potentially more so than other persistent pollutants.

There is extensive evidence of PFAS presence in many wastes. Wastewaters often contain PFAS in notable concentrations (Lenka, Kah and Padhye, 2021). Sources include industrial and landfill influent sources and ongoing excretion by humans as they are exposed to everyday consumer goods and contaminant sources (O'Connor *et al.*, 2022; Thompson *et al.*, 2023). Treatment only leads to limited removal with concentrations often increasing in effluent as PFAS precursors are degraded (Lenka, Kah and Padhye, 2021). PFAS can both partition into the solid sludges or remain in the aqueous phase, often being more mobile with shorter carbon chain lengths (Fredriksson *et al.*, 2022).

PFAS have been used extensively in food packaging for their moisture and grease repellent properties (Glenn *et al.*, 2021). This presents two difficulties. First, PFAS can be retained in any recycled application of the packaging, serving no direct function but providing a potential added substance risk for the food stored in the packaging (Curtzwiler *et al.*, 2021). For example, the occurrence of PFAS in marine plastic litter raises potential concerns for recycling ocean or ocean-bound plastic into food-contact applications (Gómez *et al.*, 2021). Secondly, composting fibrous biodegradable packaging and food utensils, which commonly contain high levels of PFAS (Yuan *et al.*, 2016), is found to contribute greatly to PFAS in compost (Choi *et al.*, 2019). To a lesser degree, food waste will also contain PFAS, with a study in the United States of America reporting PFAS in 14 out of 25 food waste samples, predominantly of the perfluorobutanoic acid (PFBA) congener (range 0.11–1 µg/kg ww) (MacRae *et al.*, 2020). Coupled with this is an extensive and growing body of literature reporting the occurrence of different PFAS in food matrices, and hence the potential to persist in food waste.

Irrigation with reused water or treated wastewater has been implicated in soil contamination with PFAS in several countries (Costello and Lee, 2020). Shorter-chain PFAS forms appear to have preferential uptake into plants from soil and irrigation water (Brendel *et al.*, 2018; Scher *et al.*, 2018; Liu *et al.*, 2019; Zhang *et al.*, 2020). In a study of corn and fescue feed crops, PFBA was reported to increase when irrigated with treated wastewater compared to groundwater sources (Mroczko *et al.*, 2021). Furthermore, recycled water use in controlled environment agriculture presents a concern as PFAS potentially transfer from hydroponic media to edible parts of leafy and fruiting vegetables (Gu *et al.*, 2023), while longer-chain forms have high bioaccumulation rates into fish (Burkhard, 2021)

Longer-chain PFAS tend to partition to solids, such as in wastewater treatment sludge (Coggan *et al.*, 2019), and consequently, present a concern in solid organic materials applied to land.

BOX 9 (cont.)

PER- AND POLYFLUOROALKYL SUBSTANCES – THE CONTAMINANT OF CONCERN FOR THE CIRCULAR ECONOMY

As an example, in Germany, paper-waste-contaminated sludge mixed into composts was implicated in the contamination of agricultural soils with a broad range of PFAS classes, including perfluorooctane sulphonic acid (PFOS), perfluorooctanoic acid (PFOA) and diPAPs (Bugsel and Zwiener, 2020). Studies of commercial composts have reported notable PFAS concentrations (Lazcano *et al.*, 2020; Sivaram *et al.*, 2022), including results indicating a high level of PFAS precursor compounds. Finally, biogas production digestate was reported to retain PFAS which were transferred into edible mushrooms when grown on this recycled substrate (Nesse *et al.*, 2023).

There is emerging evidence that PFAS also present a concern in the valorization of food waste for insect production. A study of black soldier fly larvae raised on substrate containing four PFAS congeners found that, on average, the larvae accumulated between 2 to 9 times the concentration of each congener spiked in the substrate (Jensen *et al.*, 2022). Furthermore, black solider fly larvae were found to concentrate hydrogen-substituted polyfluoroalkyl carboxylic acids that transferred from an almond hull substrate (Li and Bischel, 2022).

PFAS hazard characterization is still a developing field, with animal toxicity and human epidemiology studies only targeted to a small proportion of the known congeners in use and in the environment, limiting robust risk assessment (Fenton *et al.*, 2021). However, there is a recognition of the ability of different PFAS to persist, migrate and potentially accumulate in food through different methods of circularity in the agrifood sector. Consequently, supporting a transformation to circularity requires an increased focus on PFAS hazard characterization to support gaps in risk assessment.

Sources: See References.

Members of a youth group prepare organic compost at a farm in Kenya.

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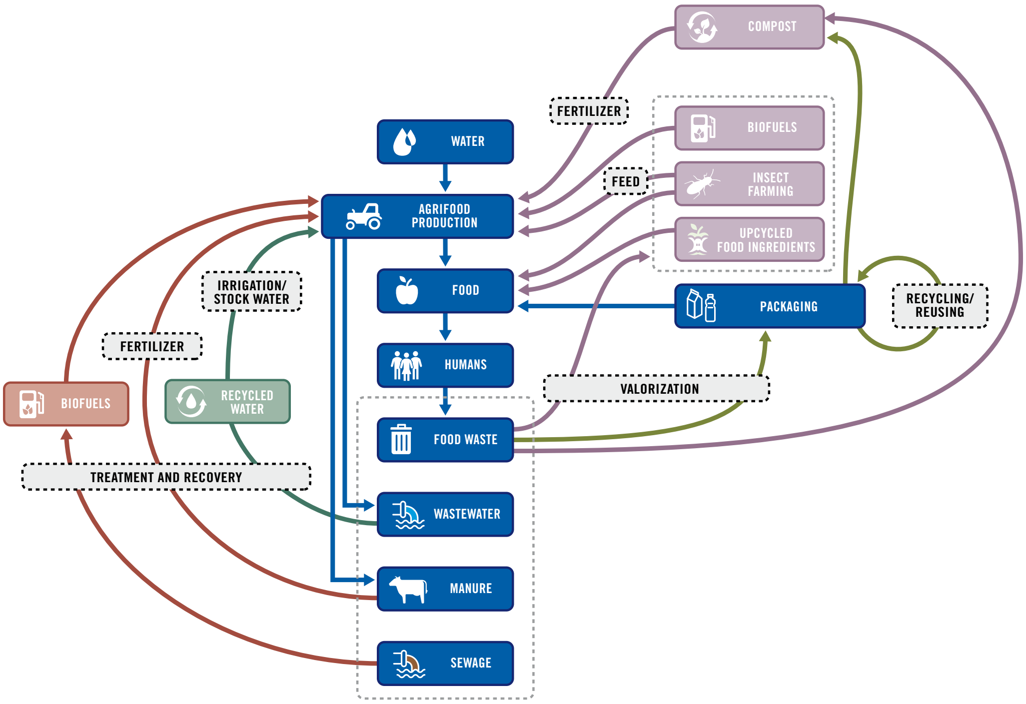
FIGURE 8. **INTERCONNECTED LINEAR AND CIRCULAR MODELS IN AGRIFOOD PRODUCTION**



Notes: **Blue** boxes and lines reflect the existing linear processes. **Purple**, **green**, **moss green** and **red** boxes and lines represent circular processes. **Grey** boxes detail the processes in use.

CHAPTER 7

POLICY CONSIDERATIONS AND A WAY FORWARD

Many countries have begun, or are considering, a transformation to circular production processes to improve the environmental sustainability of the agrifood sector and maintain food security. However, as it has been illustrated through the case studies in this report, this presents potential food safety risks. In particular, transforming to models that utilize waste products, be they wastewater, food waste, organic material or packaging, presents risks due to the chemical, microbial and physical contaminants these waste products may contain or generate. Contemporary food safety principles are grounded in good hygienic practice (FAO and WHO, 2022) that allows for circular processes and policies, particularly through fit-for-purpose risk management. However, the transformation to a circular agrifood system necessitates a shift in perspective away from the accepted food safety approaches under linear processes that include, for example, a reliance on virgin raw materials and discarding all wastes. While precaution should not hinder efforts to increase circularity in agrifood systems, failure to suitably address risks could potentially increase the foodborne disease burden. This would be detrimental to progress, as producers, consumers and trading partners could lose trust in the food produced under circular systems. Addressing food safety as a core component in the innovation and adoption of circular processes will ensure that risks are characterized and that risk management controls are validated in tandem. Areas of focus on food safety throughout circular agrifood systems are identified in Figure 9. Regulating for food safety in a circular economy includes the following measures:

- Identifying emerging issues to inform risk assessments on any emergent hazards.
- Creating frameworks for assessing and managing decontamination in food contact or agricultural applications.
- Developing appropriate guidelines and risk management measures.
- Improving consumer education and risk communication to support sustainable and safe food practices in the home.

FIGURE 9. FOOD SAFETY FOCUS AREAS FOR CIRCULAR REUSE IN AGRIFOOD SYSTEMS

USE

- Characterize risks with use
- Identify high-risk use scenarios (e.g. use of foods eaten raw, packaging of fatty foods)
- Establish controls to manage risks of pathogen/contaminant transfer to food with use
  - Functional barriers
  - Systems to use products in a manner in which no food contact occurs
  - Withholding or restricted use requirements
- Monitoring requirements to validate food safety risk
- Identify education/awareness needs for users to support safe use

PROCESS

- Validate efficacy of any treatment/decontamination:
  - Use of sentinels, and/or conservative assumptions for difficult-to-analyse analytes
- Determine fate of contaminants through the process:
  - Including any changes to bioavailability and toxicity
- Confirm quality specifications for final-use product and frequency of any quality testing

REGULATION

Food safety

- Emerging issue identification and targeted risk assessment on any emergent hazards
- Frameworks for assessing and managing decontamination in food contact/agricultural applications
- Develop health-based standards
- Education and risk communication to support sustainable and safe food practices in the home

Chemicals and waste

- Life cycle assessment to confirm fate in circular systems
- Reporting of composition of manufactured materials
- Infrastructure and treatment standards that support waste reuse in agrifood systems
- Waste collection and segregation tools
- Monitoring of hazards to identify emerging issues
- Regulate hazardous waste treatment and disposal

INNOVATION

- Adopt “safe-by-design” principles for research and development
- Food safety assessed as an equivalent target to sustainability and economic performance
- Innovation in product redesign, or promotion of changes to consumer practices, can also target the implications for end-use food safety

FEEDSTOCK

- Identify contaminants/pathogens of concern:
  - Could draw from existing monitoring, published literature or national/international guidelines and regulations
- Characterize contaminant occurrence:
  - Including identifying high-risk feedstocks, maybe on a source, spatial or temporal basis.
  - Use of sentinels for difficult-to-analyse analytes
- Identify and use management tools to segregate high-risk feedstocks

7.1 FOOD SAFETY IMPLICATIONS IN CIRCULAR AGRIFOOD SYSTEMS

As outlined in the previous sections of this report, food safety hazards in circular agrifood systems can be present in feedstock, processed material and final products and these hazards have varying implications for food safety.

> Pathogens, through occurrence in organic waste streams, can persist through treatment and processing and occur in the end product. Here, they present a high risk if transferred to food eaten raw or uncooked. ARGs are reported to be present in waste stream microbes and, through occurrence in pathogens or horizontal gene transfer, may reduce the efficacy of antibiotics to treat foodborne illnesses.

> Parasites may be transferred between hosts when animal waste or food waste are used and in integrated farming systems. Uncooked food produced in these systems presents a potential infection risk.

> Contaminants are commonly introduced, persist or can be formed in waste streams and can be produced in treatment and processing. Unsegregated feedstock can contain a wide range of chemical contaminants. Chemicals may be taken up into crops or animals, or migrate from food-contact uses, with the potential for accumulation into the food supply.

> Physical contamination can occur in solid waste streams, with potential transfer into final products. Physical fragments in food will present a direct risk of injury, as well as a potential source for contaminant migration.

> Reuse of bioactive or food-based waste components could allow allergens and pathogens to persist in future food or food-contact applications.

> Treatment and decontamination are tools to manage pathogens and chemical contaminants, although efficacy data for many such tools is lacking.

Consumers aspiring to live more sustainably may adopt inappropriate food purchasing, preparation and storage practices that pose food safety risks.

7.2 RISK ASSESSMENT AND REGULATION: THREE CASE STUDIES

Drawing from experiences in the adoption of circular practices in agrifood systems provides valuable insights into the identification, characterization and management of food safety risks. The following case studies outline how food safety has been supported in the adoption of circularity in agrifood systems. They address three angles: investigations to identify emerging issues in the use of wastewater in agriculture; risk assessment on water recovery and reuse in different food sectors; and regulation on recycled materials in food packaging.

CASE STUDY: RECYCLED WATER USE IN ALGERIA

Water scarcity in Algeria has been increasing for decades and is likely to worsen with climate change impacts (Djillali *et al.*, 2020). The use of treated wastewater for agricultural purposes is one of the principal strategies in water resource management in Algeria and has the potential to protect and preserve surface and underground water resources. However, the impact of using treated wastewater for irrigation in Algeria was not well understood. To evaluate the opportunities and implications of using treated wastewater for irrigation in Algeria, two investigations were carried out.

The first investigation was an experimental study evaluating the short-term impact of using wastewater treated for microbial pathogens for irrigation, including assessing the effect on morphological and agronomical parameters of the plants, soil physicochemical properties and the accumulation of heavy metals in soil and different parts of the plant (Djillali *et al.*, 2020). Strawberries were irrigated in a tunnel greenhouse, some with well water and some with treated wastewater. A statistically significant difference was observed in the fruit production of the plants irrigated with each water type, with higher production identified for crops irrigated with treated wastewater. Differences in the accumulation of heavy metals in soil were not statistically significant for cadmium, lead and zinc. However, copper concentrations were statistically higher in soil irrigated with conventional water. Concentrations of heavy metals in the strawberries were significantly higher when irrigated with treated wastewater but were reported to be within Codex Alimentarius maximum levels.

Policy makers discussing food safety at FAO Headquarters, Italy.

©FAO/Alessandra Benedetti

A second investigation aimed to understand the long-term effect of using treated wastewater for irrigation (Djillali, 2020). Researchers monitored a vineyard for two years where a portion of the vines had been irrigated with untreated wastewater and another portion with treated wastewater for the prior 15 years. The analysis focused on the accumulation of heavy metals in soil, plants and derived products (namely grape juice). The long-term application of wastewater, whether treated or untreated, was reported to have resulted in a significant accumulation of heavy metals in the soil. Analysis of the grape juice showed that grapes irrigated with treated wastewater accumulated heavy metal concentrations, with maximum chromium and lead concentrations of 6.2 mg/kg and 16.4 mg/kg, respectively. The study concluded that the usage of treated water for crop irrigation could help mitigate or even reduce the water deficit in Algeria, but that appropriate management and periodic monitoring of treated wastewater, soil and agricultural products are required to limit risks.

CASE STUDY: JOINT FAO/WHO EXPERT MEETING ON MICROBIOLOGICAL RISK ASSESSMENT – OPINIONS ON WATER REUSE

Acknowledging the need to implement more environmentally sustainable practices for the management and efficient use and reuse of water resources in the agrifood system, the Codex Committee on Food Hygiene approved the development of guidelines for the safe use and reuse of water in food production (FAO and WHO, 2020). To support these guidelines with scientific advice, the Joint FAO/WHO Expert Meeting on Microbiological Risk Assessment (JEMRA) published microbiological risk assessments on water reuse with fresh fruit and vegetables, dairy products and fish and fishery products, as well as in food establishments (FAO and WHO, 2019a, 2021, 2023a, 2023b).

The reports highlight the opportunity for water recovery and reuse in different food sectors. An emphasis is placed on risk assessment in the design of water-reuse systems, which relies on understanding the microbiological characteristics of raw materials and the production environment. Testing these reusable sources with microbiological assays is recommended and guidance is provided on potential indicator organisms for the determination of water quality.

Delineating the level of water quality required in a reuse scenario, be it potable or fit-for-purpose, and designing robust treatment regimens to meet the required microbiological specification is recommended during implementation. Testing to validate consistent system performance in delivering the required specification of water reuse should also be adopted after operationalization. Finally, an ongoing monitoring procedure, verification regime and enactment of contingency plans are all recommended.

Considering the different pathogens present in various water sources, the reports present guidance on determining microbiological specifications and examples of risk reductions, as well as collating case studies of reuse scenarios and supporting risk assessments. It is noted in all the reports that there are data gaps and that many of the water reuse streams are not well characterized in terms of microbiological risk. Recommendations are for regulators to be engaged with industry in supporting and regulating safe water reuse.

CASE STUDY: RECYCLED PLASTIC MATERIALS AND ARTICLES INTENDED TO COME INTO CONTACT WITH FOODS IN EUROPE

In 2018, the European Union released a strategy for plastics in a circular economy, which outlines a path forward for increasing and improving plastic recyclability, reducing plastic waste and littering, supporting innovation and investment in a circular plastics value chain, and building international cooperation (EC, 2018). The role of recycled plastics in food packaging is acknowledged through a drive for higher quality standards and potential measures to track contaminants in recycled streams.

With the increase of recycled plastic in food packaging, the critical need to achieve a high level of health protection is widely acknowledged. Supporting this is the adoption of a regulation (Commission Regulation [EU] 2022/1616) that establishes criteria for food-contact uses of recycled materials. This includes outlining suitable recycling technologies and procedures for collection and pre-processing, decontamination, post-processing and use. Furthermore, the regulation outlines the necessary information requirements for developing and listing novel technologies.

At present, the recycling technologies suitable for food contact materials are post-consumer mechanical polyethylene terephthalate (PET) recycling, where this contains a maximum of 5 percent materials that were used in contact with non-food materials or substances, and recycling from product loops which are in a closed and controlled chain.

Food safety risk assessment of plastic recycling processes is undertaken by the European Food Safety Authority (EFSA) before any process can be adopted for food packaging uses. Published assessments for PET recycling processes have evaluated the decontamination efficiency on surrogate contaminants using a risk assessment model designed to be protective of the potential exposure to an infant consuming water from a recycled PET bottle (EFSA CEF Panel, 2011).

7.3 CONSUMER BEHAVIOUR

Under SDG 12 (Ensure sustainable consumption and production patterns) is a target for 2030 to "ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature" (UN, 2015). Consequently, an important policy consideration relates to supporting consumers to change food purchasing, handling, preparation and storage practices, aligned with an increasing awareness of sustainable lifestyles. Growing awareness of environmental and social sustainability issues is increasingly shifting consumer practices to incorporate circularity in decision-making, consumption patterns and home practices (Civero *et al.*, 2021). Household waste represents a high proportion of total waste volume. Supporting this shift in behaviour will be critical for enacting circular systems. Furthermore, consumers often play a key role in correctly segregating waste for recycle or reuse chains, as well as practicing waste recycling at home, for instance by composting, collecting and reusing greywater, and feeding food wastes and food by-products to smallholding livestock.

Good food safety practices in the home are an important means of mitigating the high proportion of foodborne illness that are attributed to improper food handling (Menini *et al.*, 2022; Yemane and Tamene, 2022). Adopting behaviours to support circularity in the home, however, has the potential to conflict with advised food safety practices. Consequently, it is important that regulatory authorities understand how adopting inappropriate circular practices or decision-making in the home compromises food safety and direct educational resources to preventing this.

Food wastage can be limited by avoiding throwing out food that is still fit for consumption. However, this presents a challenge for food safety, as consumer recognition of shelf life for food safety purposes (the “use by” date) as opposed to quality purposes (the “best before” date) is often poor (Kavanagh and Quinlan, 2020). Furthermore, the tools available at home to support decision-making around whether food is still fit for consumption are limited. Such decisions often rely on visible mould, spoilage or off-smells, which are not necessarily effective means for detecting pathogen or mycotoxin presence. A desire to limit waste may also see visibly spoiled or mouldy parts cut or scraped off and the rest of the food consumed, despite the potential for mycotoxin formation and diffusion into areas without visible contamination (Matumba *et al.*, 2016; Olsen, Gidlund and Sulyok, 2017).

People having lunch in Italy.

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Similarly, consumers are at risk of exposure to phytotoxins if they consume inappropriately stored produce, such as potato tubers that have sprouted or parts of the plant with higher toxin levels, such as apple cores, in an effort to avoid waste (Crews and Clarke, 2014; Nicholes *et al.*, 2019; EFSA CONTAM Panel, 2020).

Keeping uneaten food from out-of-home dining to eat at a later date is another practice consumers are often encouraged to adopt in order to avoid food waste (Mirosa, Liu and Mirosa, 2018). Where food is correctly packaged and stored before consumption, this is unlikely to present a concern. However, the risk of incorrect storage can result in increased microbial growth and toxin formation. Foodborne illness outbreaks have been associated with high levels of cerulide from *B. cereus* growth in rice leftovers from restaurants (Delbrassinne *et al.*, 2012).

Measures to reduce food-related waste will have consumer implications. For example, with the phasing out of single-use plastic bags, consumers are utilizing reusable shopping bags. In addition, financial incentives have been used to promote the use of reusable containers, such as reusable coffee cups. Food safety is contingent on these food contact materials remaining hygienic to avoid contamination. Replacement of kitchen plastic wraps with reusable materials such as beeswax wraps may give rise to food safety risks as they are difficult to adequately clean and sanitize, and guidance must be given so that cloths intended for reuse do not come into contact with raw meat or other animal-based foods (BfR, 2022b). For shopping bags and reusable containers, there is a risk of spillage of items, such as packaged meat juices, household chemicals and other contamination sources, on the interior surfaces. Reusing these bags to carry foods consumed raw then presents an exposure pathway for pathogens or chemical contaminants (Kasza *et al.*, 2022). A study of microbiological contamination of reusable polypropylene bags found a range of pathogens, as well as the presence of ARGs (Barbosa *et al.*, 2019). An important finding, however, was that the visual appearance of each bag was not correlated with the microbial contamination, suggesting that consumers who rely on visual cues to indicate the need to sanitize the bags may be at risk.

Consumers may adopt other home practices for circularity, bringing many of the risks associated with the adoption of circular measures described in the earlier chapters. For instance, collecting wastes, such as food waste for composting at home, if not correctly stored, may attract pests, including flies and rodents, which are vectors for foodborne pathogens. In addition, consumer behaviour can indirectly influence the food safety outcomes of other circular practices within the agrifood system. Consumer mis-sorting or inadequate cleaning of recyclable plastic packaging or storing chemical products in reusable packaging are common behaviours (Widén, Leufvén and Nielsen, 2005; Rousta and Ekström, 2013). If not addressed through further treatment in the waste system, these behaviours can introduce NIAS or other contaminants into the feedstock for reusable or recycled packaging (Horodytska, Cabanes and Fullana, 2020).

7.4 RISK COMMUNICATION

Consumer-focused initiatives to improve sustainability with food purchasing, storage and use should be founded upon an understanding of food safety practices and awareness of health risks if these practices are not maintained. Solutions that aspire to reduce food or food-related waste but result in known or potential risk may pose acute and chronic health outcomes for consumers. Furthermore, outcomes focusing on one aspect, such as reducing packaging waste, could have unforeseen impacts on increasing food waste if solutions do not maintain integrity, which can result in quicker spoilage (Marsh and Bugusu, 2007). However, there are opportunities in initiatives that increase waste in one area, such as changing packaging attributes, but still have a net benefit on waste. For example, they may support informed decision-making for purchasing or using only as much food as needed or provide steps to identify when food is spoiled or unsafe in retail and in home storage (Wikström *et al.*, 2014).

Food manufacturers and retailers as well as regulators can support consumers in adopting sustainable practices through effective risk communication on measures to prolong shelf life and in determining if food is spoiled or unsafe. Ensuring clear label date marking is also a key area for regulators and manufacturers to address to limit wastage (FAO, 2022; Patra, Feng and Howard, 2022).

With the reuse of waste streams, there is potential for a disgust factor among consumers linked to consuming foods from circular agrifood systems (Savchenko *et al.*, 2019). To avoid qualitative food loss, transparency in how any food is produced is important, particularly if environmental aspects of a circular economy are important for consumer choices, but overcoming disgust necessitates strong food safety messaging to provide assurance that health is not at risk (Aschemann-Witzel and Stangherlin, 2021).

7.5 DATA GAPS AND RESEARCH NEEDS

For the transformation to circular agrifood systems to be successful, it must address many uncertainties related to potential food safety impacts. Much of the understanding in relation to food safety risks derives from linear processes, where waste is removed from the system. Hence, recirculation and reuse of waste presents a challenge in terms of understanding the fate and ultimate risk involved. Innovation in circular systems has often been supported with only limited research into food safety (Bonwick *et al.*, 2019), and there has been little focus on the risks that can emerge and accumulate in circular approaches (Focker *et al.*, 2022). For example, in a broad literature review on emerging risks for plant, animal and human health from novel foods and feeds in the framework of a circular economy, only 26 primary studies were identified that investigated risks, compared to over 1 000 studies that did not (EFSA, 2022). Addressing these data gaps would underpin robust risk assessment and management of food safety risks in circular agrifood systems.

The data gaps on microbiological risks include:

- survival and internalization of pathogens in crops when introduced through circular processes into soil or irrigation water;
- new points of entry of pathogens into closed-loop systems;
- potential exposure to emerging or opportunistic pathogens, particularly with use of novel water or feedstock sources;
- survival of pathogens through valorization, including in insects raised on food wastes;
- risks related to ARGs, particularly where antibiotics co-occur in the feedstock;
- significance of parasites, particularly through the completion of heteroxenous life cycles if the hosts are being raised in a single system; and
- efficacy of pathogen decontamination techniques.

For chemical contaminants, data gaps include:

- identification and characterization of NIAS in packaging materials and migration to food in reused packaging;
- the fate and accumulation of PFAS through circular agrifood systems and characterization of the resulting health risk;
- characterization of the health risk of micro- and nanoplastics, as both a physical concern and a source for migration of NIAS into food;
- emerging contaminant hazard characterization and quantifying uptake into food crops, especially under changing climate conditions;
- natural toxin persistence and transformation in circular systems;
- amplification of contaminants in circular systems and best practices to reduce this;
- chemical migration from smart or active packaging and the persistence of active packaging chemicals in recycling streams;
- allergenic potential of biopolymers and retention of allergens through circular systems; and
- efficacy of chemical decontamination techniques.

Addressing many of these data gaps requires targeted research to improve the risk characterization in adopting circular processes as well as the fate of these contaminants. As identified by the case studies, until specific data are available, conservative models and assumptions can be used to ensure consumer protection.

For example, when recycled water is used for livestock drinking water, management controls can be established to limit sources where uncertainty prevents risks from being conclusively deemed acceptable (Poppenga *et al.*, 2018).

Achieving enhanced environmental sustainability and economic performance outcomes are seen as drivers in the transformation to circular production processes, while the inability to provide assurances for food safety, and consequently for consumer health, is a key risk to any gains made. The role that food safety considerations must play throughout the process of innovation and transformation towards circular agrifood systems must be emphasized, and it is crucial that this be integrated into research and implementation programmes from the outset.

7.6 PLACING FOOD SAFETY AT THE CORE OF CIRCULAR AGRIFOOD SYSTEMS

Transforming to circular production processes requires systemic changes in agrifood systems. There are clear economic and environmental drivers for increasing circularity. However, the force of these drivers must be counterbalanced with the need for food to be safe to eat. Consequently, an integrated approach is necessary to address food safety as a core component in the innovation, development and implementation of circular approaches.

Although a fully closed loop with little or no waste is the ideal, it is likely that some form of segregation to exclude hazardous contaminants from agrifood systems is necessary, at least while these persist in current use or as legacy issues in society. Measures to assess and manage pathogens will also be necessary, due to the ease with which waste streams are microbiologically contaminated. Further to established concerns, the adoption of circular practices has the potential to facilitate the emergence of risks, be these related to microplastics, ARGs or novel pathogens and contaminants, with unclear consequences in the absence of further research. This necessitates ongoing horizon-scanning and review of risks to ensure early action is taken to mitigate emerging risks. Such measures can be supported by increasing the coverage of risk assessments to include aspects of circular production processes, such as the reuse of water in agrifood systems, which has been assessed by FAO and WHO and for which case studies exist from several countries (FAO and WHO, 2019a, 2021, 2023a, 2023b).

There is little research into the food safety risks in innovating and adopting circular agrifood systems, compared to the research outputs on the environmentally sustainable or economic outcomes of such systems (Aschemann-Witzel and Stangherlin, 2021). Adopting a “safe-by-design” approach ensures that food safety risks are characterized throughout the research and adoption of circular processes, underpinning assurances that the resulting food is safe when produced or packaged using the new approaches. Innovation to enhance food safety in circular agrifood systems is needed throughout the system and should be supported through innovation ecosystems to conceptualize, develop and disseminate the technology and knowledge (Klerkx and Begemann, 2020). There are roles for researchers, farmers, product and food manufacturers, regulators and consumers in supporting the transformation to safe circular agrifood systems, and food safety considerations should be included in all relevant initiatives and national research funding. Underpinning technological and process changes is a need for behavioural and social change to bring about a circular mentality regarding agrifood systems. Ingraining the criticality of food safety into the behavioural transformation, through education and other ways of nudging actors, will ensure that gains towards sustainability and food safety are consolidated.

Although characterizing risks to food safety has been emphasized, there are also opportunities to develop and adopt circular processes that improve food safety outcomes, either directly – through the introduction of new materials with reduced risk profiles or valorization processes that treat known risks to produce a safer food product, or indirectly – through the economic or societal pressure to phase-out contaminants that persist in circular systems.

National and international regulation and guidance can be developed and adapted to support the transformation to circular production. Ensuring that clear guidelines are in place to assess and manage food safety risks and that regulations adequately cover the new uses of waste materials in agrifood systems, enables a proactive approach to maintaining food safety in transforming economies. Agricultural and food safety legislation must also align with chemical approval and waste legislation to support life cycle assessment and good management of waste infrastructure and treatment.

There is also a role for extension and advisory services to provide advice on regulations and best practices on the safe use of circular feedstocks and on the reduction of food and food packaging waste in the retail sector and by households. It is critical that such approaches be undertaken with a gender perspective. According to the Organisation for Economic Co-operation and Development (OECD) (2020), women are more likely to experience the negative effects of unsustainable production and the impacts of environmental degradation, due to their high participation in waste management and their often-inadequate labour conditions. However, women are also key actors in moving towards sustainable patterns, for example by leveraging local value chains for sustainability and being more likely to recycle and minimize waste. Current guidance, such as the FAO Voluntary Code of Conduct for Food Loss and Waste Reduction (FAO, 2022b), outlines as a key guiding principle the importance of recognizing the vital role of women in achieving sustainable development and reducing food loss and waste.

Food safety regulation must enable and support agrifood systems transformation. Ensuring that environmental sustainability and economic performance balances with food safety means that regulation for food safety should be commensurate with the risk and not pose a barrier to a more environmentally sustainable system.

Many aspects of a food safety regulatory system result in environmentally unsustainable processes including:

> labelling requirements resulting in packaging wastage;
> judging food products unfit for human or animal consumption due to the presence or potential presence of unexpected contaminants, allergens or pathogens;
> holding or rejecting consignments of perishable foods or feed while regulatory decision-making is pending;
> regulatory barriers for valorization of food wastes or food by-product wastes for food and feed uses;

- setting inflexible shelf life and storage requirements;
- restrictions on technologies that present opportunities to manage safety together with sustainability, for example irradiation to manage pathogens and increase shelf life without chemical usage;
- destructive laboratory testing, in particular if this leads to additional damage or loss of value in the food; and
- single-use requirements for sampling and analytical testing of consumables.

Despite being environmentally unsustainable, the above measures are justified where the failure to take action results in unsafe food. However, they do not preclude the consideration of alternatives or innovation to reduce this waste burden and manage any waste through circular approaches. Examples include the use of rapid risk assessment methods for unexpected contaminants, where conservative parameters are used to allow rapid decision-making, as opposed to rejection and waste of food consignments (FAO and WHO, 2019b). Reprocessing food to reduce or treat the contaminants may also be favourable to reduce the levels of food going to waste.

It is important that food safety legislation is well-designed and efficiently implemented. A study of integrated crop and livestock farming systems found that food safety regulations could inhibit adopting circularity (Garrett *et al.*, 2020), emphasizing the need to reassess standards, particularly where these are out-dated, and increase the flexibility of regulations to limit food wastage where eventuation of a risk is unlikely (FAO, 2022). For example, leniency could be placed on pathogen levels in food to be cooked, with emphasis given to consumer education as opposed to wasting food that will be made safe with good kitchen hygiene.

Internationally traded foods must traverse different national regulations, with varying levels of protection against risks. Consequently, food deemed safe in one country can be considered unsafe in another and hence could be wasted. Reducing this waste places an emphasis on countries developing standards commensurate with risk informed by sound science. Operating within and harmonizing with the Codex Alimentarius food safety standards ensures a common and transparent approach to food safety regulation and consequently limits wastage in trade (FAO, 2022).

Producer checks the quality of water at an aquaponics farm in Italy.

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CHAPTER 8

CONCLUSION

Ensuring safe, affordable and healthy diets for all, amid the challenges of a growing global population and climate change, requires informed action to transform our agrifood systems and place them on a sustainable trajectory. Many initiatives across water, waste, packaging and consumer education are already underway as this transformation progresses. However, there is an imperative to place food safety as a key priority within the circular agrifood system transformation.

The adoption of circular production practices necessitates the review of risk profiles for food production, processing, retail and consumption as the feedstocks, processes and end products of these systems can differ considerably in food safety hazards from those in a linear system. Microbiological, chemical and physical contaminants are known to persist in certain waste streams and by-products, which through reuse or valorization could exacerbate existing issues or cause new risks to emerge. Failure to address food safety risks in adopting circular production processes can lead to an increased disease burden and set back efforts to adopt sustainable initiatives. All levels of the food supply chain, from producer to consumer, including regulators, have a role to play in ensuring food safety during the transformation to circular agrifood systems.

Although research into food safety outcomes remains limited, resources such as guidelines and case studies are increasingly available to support adopters of circular production in assessing food safety (FAO and WHO, 2019a, 2021, 2023a, 2023b). Foresight and horizon scanning are critical to ensure emerging risks for circular agrifood systems are identified and assessed in a proactive manner (FAO, 2022a).

Going forward, innovation can be supported by addressing data gaps that limit risk assessment of circular processes and reused or recycled materials, focusing research efforts on food safety and exploring opportunities for improving food safety outcomes. Research and industry initiatives can be supported with clear regulation, which can bolster the flexibility to reduce waste while protecting food safety. Harmonization with international standards supports initiatives to prevent food waste in trade. Lastly, encouraging consumers to adopt sustainable practices is best supported through education and risk communication.

The transformation of agrifood systems to circular production processes offers remarkable promise in achieving sustainable and equitable development goals. All stakeholders in agrifood systems must be proactive in harnessing innovation and addressing food safety as a priority to advance towards resilience and sustainability while ensuring that food is safe.

A customer buying apples on sale at a fruit stall in Brazil.

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FOOD SAFETY
IN A CIRCULAR ECONOMY

Introducing circular processes and policies is one route to agrifood systems transformation, a key accelerator to achieving the Sustainable Development Goals. A circular economy represents a major departure from the current linear production system and from many assumptions underlying existing food safety approaches. *Food Safety in a Circular Economy* considers the current and emerging evidence related to food safety risks in various circular production initiatives within agrifood systems.

While circular solutions offer promising sustainability benefits, they also introduce certain food safety concerns, such as the risk of contaminants, antimicrobial resistance and physical hazards. This publication examines four areas of interest – water scarcity, food loss and waste, food packaging waste, and land use efficiency. By exploring these areas, *Food Safety in a Circular Economy* highlights the importance of addressing potential food safety issues in the context of circular agrifood systems.

Food safety policies and principles must be adapted to the unique characteristics of circular agrifood systems. Ensuring food safety requires a collective effort across all levels of the food supply chain, from producers to consumers and regulators. Each stakeholder has a critical role to play in safeguarding food safety as we move towards more sustainable agrifood systems.

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