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FOOD SAFETY IMPLICATIONS OF RECYCLED PLASTICS AND ALTERNATIVE FOOD CONTACT MATERIALS

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by

Mark Feeley

Magdalena Niegowska Conforti

Vittorio Fattori

and

Markus Lipp

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© FAO/Riccardo De Luca – Salad cultivated by aquaponic system in a plastic package.

© FAO/Giulio Napolitano – Reusing plastic bottles for drinking water at a source.

© FAO/Giulio Napolitano – A customer choosing packaged meat in a food store.

CONTENTS

Acknowledgementsiv
Abbreviations.....v
Executive summary.....vii

CHAPTER 1
INTRODUCTION..... 1
1.1 Global context of FCMs use 4

CHAPTER 2
FOOD CHEMICAL SAFETY ISSUES RELATED TO FCMs 7
2.1 Food safety considerations related to micro- and nanoplastics in FCMs..... 11
2.2 Nanomaterials in food packaging 13
2.3 Intelligent FCMs..... 15
2.4 Recycled plastics and food safety considerations 16
 2.4.1 Recommendations for ensuring food safety of recycled FCMs..... 21
2.5. Alternative materials for food packaging 23

CHAPTER 3
CONSIDERATIONS OF THE CODEX ALIMENTARIUS COMMISSION FOR FCMs.... 27

CHAPTER 4
CONCLUSIONS AND WAY FORWARD.....29

REFERENCES33

FIGURES

Figure 1. Steps of plastic recycling for food contact materials –
food safety considerations.....22
Figure 2. The main sources for bio-based food contact materials.....25

BOXES

Box 1. Food packaging market 1
Box 2. Food packaging can reduce global food waste.....2
Box 3. Status of research on the impact of micro- and nanoplastics on human health.....13
Box 4. Mechanical and chemical recycling used for plastic food contact materials 17

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ABBREVIATIONS

CAC	Codex Alimentarius Commission
CCCF	Codex Committee on Contaminants in Foods
CCEXE	Executive Committee of the Codex Alimentarius Commission
ECHA	European Chemicals Agency
EDT	Expanded Decision Tree
EFSA	European Food Safety Authority
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FCMs	Food contact materials
GHG	greenhouse gas
IAS	intentionally added substances
ILBI	international legally binding instrument
ECFA	Joint FAO/WHO Expert Committee on Food Additives
JMPR	Joint FAO/WHO Meeting on Pesticide Residues
MSW	municipal solid waste
NIAS	non-intentionally added substances
OECD	Organisation for Economic Co-operation and Development
OML	overall migration limit
SMLs	specific migration limits
TTC	threshold of toxicological concern
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
US FDA	United States Food and Drug Administration
WHO	World Health Organization

NAMES OF CHEMICAL SUBSTANCES

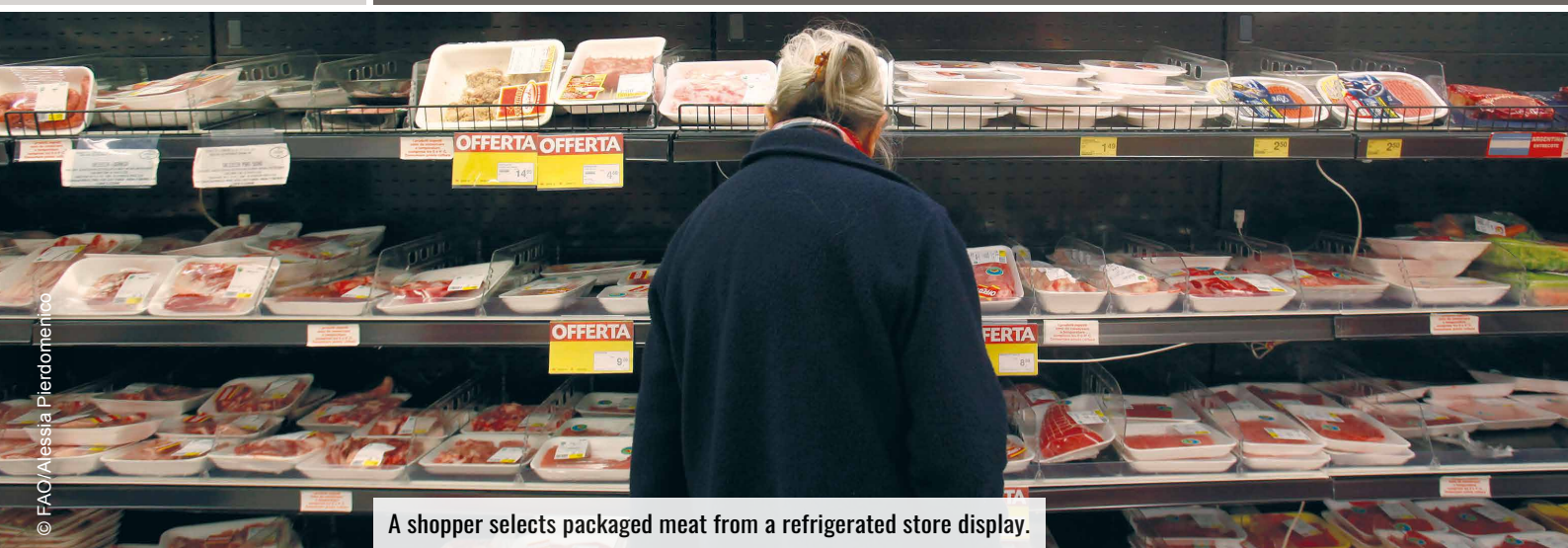
CO₂	carbon dioxide
HDPE	high density polyethylene
LDPE	low density polyethylene
PA	polyamide
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PCDD/Fs	polychlorinated dibenzo- <i>p</i> -dioxins and polychlorinated dibenzofurans
PE	polyethylene
PET	polyethylene terephthalate
PFAS	per- and polyfluoroalkyl substances
PHAs	polyhydroxyalkanoates
PHBs	polyhydroxybutyrates
PLA	polylactic acid
PP	polypropylene
PS	polystyrene
PVC	polyvinyl chloride

EXECUTIVE SUMMARY

Food contact materials (FCMs) play a vital role in helping to reduce food waste, with more than two-thirds of all packaging materials produced reported to be used in the food and beverage sector. The production of FCMs from plastic polymers has contributed to a global plastic waste epidemic. To address the growing environmental and potential human health concerns of plastic waste, efforts are underway to increase recycling rates and investigate alternative materials that can be used to produce FCMs from renewable resources.

Although approved mechanical and chemical recycling processes exist for certain plastic polymers, chemical risks may arise when plastic waste streams are poorly controlled, leading to mixing of non-food-contact and food-contact plastics, food packaging materials subjected to post-consumer misuse, and the introduction of non-intentionally added substances (NIAS) during recycling. Studies on chemical migration from different recycled plastics, including recycled FCMs, have reported the release of harmful chemical substances such as metals, brominated flame retardants, persistent organic pollutants (POPs), and phthalates from recycled plastic products at higher quantities compared to virgin plastics. In addition, decomposition and reaction products of intentionally added substances (IAS), such as surfactants, coatings, lubricants, antioxidants, thermal stabilizers, and biocides, can also be subject to migration from a variety of recycled plastics, including FCMs. To address the concern of migration of both NIAS and IAS from recycled plastic materials, approved recycling processes rely on extensive cleaning of post-consumer plastic waste and the use of chemical surrogates designed to demonstrate the effective removal of a spectrum of chemicals, including those associated with possible consumer misuse. Specific chemical migration limits based on structural properties related to chemical toxicity can then be used to assess identified migrating substances with little or no hazard data. For migrating substances with unresolved chemical structures, a threshold of toxicological concern (TTC) approach also offers a pragmatic solution to assess the various chemicals that can migrate into food from both virgin and recycled plastics. The TTC approach can be used in evaluating potential human health risks from exposure to low levels of chemicals when toxicity data are limited or not readily available, and is currently in use by various regulatory agencies in the evaluation of FCMs, flavouring substances, cosmetics and consumer products, and impurities in pharmaceuticals.

The use of alternative FCMs such as bioplastics is increasing. These are produced from renewable resources with potentially better decomposition and degradation properties compared to fossil fuel-based plastics; however, they can present specific chemical risks related to both the source of the feedstock and the inherent properties of the starting biological material. In a similar fashion, the increased development and use of smart FCMs can involve the possible migration of unique chemicals



A shopper selects packaged meat from a refrigerated store display.

intentionally added, that interact or remain in direct contact with food for a specific purpose. Smart FCMs involve compounds, for example, nanomaterials, that are intentionally incorporated into the FCM matrix to extend food shelf life, improve food quality, or enable real-time monitoring of freshness and safety. All these issues would need to be considered during product development and assessed during the premarket approval process.

Exposure to micro- and nanoplastics from food and beverages is an area of high public concern. Several factors, including the lack of validated analytical methods for the detection and identification of micro- and nanoparticles, have so far prevented regulatory agencies from identifying a clear risk from micro- and nanoplastics to human health. This is considered a rapidly evolving area, with future research being developed to address the identified data gaps. Microplastics are not unique to recycled plastics but are a possible outcome of physical plastic recycling practices.

Given the absence of globally harmonized standards to ensure the safety of recycled plastics used in food packaging, the Codex Alimentarius Commission (CAC) requested that Member Countries indicate whether guidance on food safety considerations for recycled plastics would be beneficial and, if so, to share information on their national programmes and current practices regarding the use of recycled FCMs. Feedback from Codex Members has shown broad interest in pursuing this work. The Codex Committee on Contaminants in Foods (CCCF) agreed to prepare a discussion paper for its Nineteenth Session (CCCF19) on developing guidance related to food safety considerations for the use of recycled materials in food packaging (FAO and WHO, 2025). If the proposal is approved, the guidance will focus on food safety aspects associated with the use of recycled plastics, particularly the potential for food contamination, and on their safe use in food packaging.

This document aims to describe the possible food safety implications of recycled plastic FCMs and FCMs produced using alternative bio-based materials and associated technologies, in the context of existing regulatory structures for reviewing FCMs. The timely evaluation of food safety issues related to recycled and alternative FCMs will enable this area to reach its full potential while protecting consumer health and ensuring fair trade.

CHAPTER 1

INTRODUCTION

FCMs comprise a diverse category of manufactured materials that typically include food processing equipment, food preparation surfaces, food transportation containers, cookware and direct food packaging and its components. In this document, FCMs do not include agricultural plastics used in crop production, such as mulch films, greenhouse films, irrigation tubing, silage wraps, seedling trays, etc., nor do they include materials used in the capture or farming of aquatic products. For FCMs produced for direct or primary food contact (**Box 1**), the most commonly used materials in production are paper and cardboard, metals, glass, ceramics and plastics. Globally, paper and cardboard account for an estimated 34 percent of food packaging materials, while glass and metals represent 11 and 6 percent, respectively. Plastics dominate, making up 37 percent of food packaging materials (Severin *et al.*, 2023). Over two-thirds of all packaging materials produced are reportedly used in the food and beverage industries (Ncube *et al.*, 2020), and, in the plastic industry, single-use plastics account for a 50 percent proportion of total plastic production (Tan, Cui and Xi, 2021). The food sector is the largest consumer of single-use packaging, accounting for up to 35 percent of global packaging production, with approximately 85 percent ending up in landfills or as mismanaged waste.

BOX 1

FOOD PACKAGING MARKET

In 2024, the global food packaging market was estimated at USD 505.27 billion, with a compound annual growth rate of 6.26 percent. By 2032, the same market is projected to grow to USD 815.51 billion. Asia Pacific leads globally with a market share of 32.97 percent in 2024.¹ Worldwide, the total estimated value of the packaged food market was over USD 1.9 trillion in 2020 and is expected to exceed USD 3.4 trillion by 2030, based on a 5 percent annual growth rate (Kumar and Prasad, 2021).

FCMs, specifically primary food packaging, i.e. the first layer of packaging that comes into direct contact with food, play a critical role in helping to maintain a safe food supply and in reducing food loss and waste (**Box 2**). The primary purposes of food packaging are to protect foods from physical, chemical, and microbial hazards and to prolong shelf life. Consequently, food packaging directly contributes

¹ For more details see <https://www.fortunebusinessinsights.com/industry-reports/food-packaging-market-101941>

to minimizing food loss and waste (FAO, 2024). Food packaging labelling also serves as a key vehicle for conveying essential information to consumers, including nutritional values, ingredients of processed foods and allergen information (Alamri *et al.*, 2021). Discussions on food packaging functions and technologies that are specifically designed to reduce food waste can be found in Wikström *et al.* (2018, 2019). Additional ways to reduce food loss and waste through packaging include developing new packaging materials and designs to better protect food and improve handling, usability, and shelf life (Uhlig *et al.*, 2025). The production and use of FCMs or food packaging can be considered as a coordinated system for preparing foods for post-collection or harvest handling, storage, effective distribution and delivery to consumers (Saha, 2022).

BOX 2**FOOD PACKAGING CAN REDUCE GLOBAL FOOD WASTE**

Food packaging, including plastics and alternative materials, can significantly contribute to reducing food waste, thereby lowering food production costs, enhancing the overall efficiency of the food system, improving food security and nutrition, and promoting a more environmentally sustainable food system (FAO, 2019). Global food waste has been estimated at almost USD 1 trillion every year, or 1.05 billion tonnes of food, while also generating an estimated 8–10 percent of global greenhouse gas (GHG) emissions (UNEP, 2024). Previous estimates have placed the amount of food produced globally that is lost at the retail and consumer stages at 17 percent of the total food produced (FAO, 2019; UNEP, 2021). Additional details on the extent of global food waste can be found in the United Nations Environment Programme (UNEP) Food Waste Index Reports (UNEP, 2021, 2024).

Regulations addressing the premarket food safety aspects of FCMs have been developed and are used by numerous countries worldwide. These regulations or guidelines ensure that any FCM is safe for use and that the possible migration of chemical substances – whether intentionally used in manufacture or unintentionally present – has been evaluated and determined not to pose a human health concern. Regulations on FCMs worldwide have been described as quite heterogeneous (de la Cruz García, Moragas and Nordqvist, 2023). One of the main focuses of FCM regulations is preventing the migration of chemical compounds from packaging polymers into food systems at levels that pose a health concern. New challenges in FCM regulations arise with emerging technologies, including plastics recycling and FCMs made from alternative non-synthetic materials. These materials are referred to as alternative plastics. An additional area of innovation in FCMs involves smart packaging technologies. Smart packaging includes both active packaging and intelligent packaging. Active packaging uses components that can absorb unwanted substances (e.g. moisture, oxygen, ethylene) or release beneficial agents, such as antioxidants and antimicrobials, into the packaging environment (Soltani Firouz, Mohi-Alden and Omid, 2021). Intelligent packaging uses embedded indicators, sensors and tracking systems that can monitor environmental conditions, such as pH, temperature, and humidity, and provide real-time feedback on food quality, freshness, and safety. New chemicals used in smart food packaging, as well as nanomaterials in FCMs that provide specific functional properties, will also need to be assessed for their migration potential.



Packaged prepared foods in a refrigerated retail display.

Increased production of recycled plastics for food packaging is being implemented partly to combat the growing problem of plastic waste. If not properly controlled, recycling and reuse of plastic FCMs may lead to increased exposure to packaging components compared with virgin FCMs (Geueke *et al.*, 2025).

Although not specific to recycled FCMs alone, microplastics (plastic particles smaller than 5 mm) and even smaller nanoplastics (plastic particles less than 100 nm) have been detected in a wide variety of foods, leading to human exposure. Mechanical recycling of plastics has been identified as one of the sources of microplastic pollution in the environment (Suzuki *et al.*, 2022), which can then contribute to dietary exposure. Additional details on micro- and nanoplastics are discussed in Section 1.1.

This document aims to describe the possible food safety implications of recycled plastic FCMs and FCMs produced using alternative bio-based materials and associated technologies, in the context of existing regulatory structures for reviewing FCMs. The timely evaluation of food safety issues related to recycled and alternative FCMs will enable this area to reach its full potential while protecting consumer health and ensuring fair trade.

1.1 GLOBAL CONTEXT OF FCMs USE

While FCMs can greatly enhance food safety and reduce food waste, various issues related to the production, use, and disposal of plastics have been identified. Plastics used in FCMs not only provide an effective barrier against environmental agents, but also make transport across the supply chain more efficient due to their light weight and durability.

The versatility of plastics in creating a wide range of shapes and customizable FCM options provides another advantage that, along with the benefits mentioned above, explains their extensive use over the years. Most plastics, including those commonly used to package food and beverages, are made from petrochemical feedstocks derived from non-renewable fossil resources. Hydrocarbons are extracted from oil and natural gas to obtain the hydrogen and carbon needed to produce plastic (Geyer, Jambeck and Law, 2017). Among fossil fuel-based plastics, polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), polyethylene (PE), and polyethylene terephthalate (PET) are commonly used for food packaging (Operato *et al.*, 2025). These synthetic polymeric materials are considered the most important class of packaging materials for both food and non-food applications. This is due to their lower production cost compared to glass and metals, their versatility, and their suitability for advanced packaging technologies such as modified atmospheric packaging (Berk, 2018). While food packaging materials such as glass and metal can be efficiently recovered and are highly recyclable, several challenges related to recycling plastic FCMs, including cost, collection, sorting, decontamination, chemical safety, and material degradation, continue to hinder the implementation of a circular economy for these materials (Geueke, Groh and Muncke, 2018). The global plastic waste crisis is primarily caused by two main factors: the production and use of single-use plastic items with limited durability, and the low rates of recovery and recycling (Walker and Fequet, 2023). To achieve plastics recycling goals, most countries will need to combine legislation and policies with financial support to promote the development of recycling technologies that are efficient, equitable, and profitable within a truly sustainable economy (Jehanno *et al.*, 2025). In 2022, global plastic production totalled 400 million tonnes, but less than 10 percent of this was produced as secondary plastics through mechanical recycling (Houssini, Li and Tan, 2025).

Micro- and nanoplastic pollution is a global environmental contamination issue, with an estimated three million tonnes of microplastics entering the environment each year (Health Canada and ECCC, 2020; Zhang *et al.*, 2020).

Microplastics can be released directly into food and beverages from the use of various packaging materials, with polymers such as PET, PS, PP, and PE being susceptible to mechanical abrasion, thermal exposure, and chemical leaching (Dessi *et al.*, 2021; He *et al.*, 2021; Carullo and Farris, 2025; Liu *et al.*, 2025). A recent review identified several FCMs associated with the release of microplastics into various food matrices (Zhao *et al.*, 2026). Current evidence indicates human exposure and uptake of micro- and nanoplastics; however, due to various analytical

deficiencies, this exposure is generally considered insufficient to define an actual human health risk (Garrido Gamarro and Costanzo, 2022a; WHO, 2022; Duncan *et al.*, 2024; EFSA *et al.* 2025).

With increasing emphasis being placed on plastic recycling (Box 4), mechanical plastic recycling facilities have been shown to contribute to microplastic pollution (Gabisa, Ratanatamskul and Gheewala, 2023). The size-reduction phase of plastic recycling and related prior environmental weathering have been identified as two important factors associated with microplastic formation from plastic recycling facilities (Stapleton *et al.*, 2023). While micro- and nanoplastic release to the environment comes from a number of sources, it has been estimated that the global discharge of microplastics from mechanical plastic recycling facilities will increase from 41 kt in 2000 to 1397 kt in 2060 (Suzuki *et al.*, 2024).

Additional details on the food safety implications of micro- and nanoplastics are provided in Chapter 2.

While not the focus of this report, in 2018 more than 500 companies – representing 20 percent of all plastic packaging produced globally – committed to using 100 percent recycled, recyclable, or reusable plastic packaging in the coming years through the New Plastics Economy Global Commitment, launched by the Ellen MacArthur Foundation and the United Nations Environment Programme (UNEP). The commitment brings together businesses, governments, and other stakeholders to begin working toward building a circular economy for plastics (Ellen MacArthur Foundation and UNEP, 2023). One hundred and seventy-five nations have also endorsed a resolution at the fifth session of the United Nations Environment Assembly in March 2022² to end plastic pollution, aiming to develop an international legally binding instrument (ILBI) by 2024, also referred to as the Global Plastics Treaty. Following a recent meeting (August 2025) of the Intergovernmental Negotiating Committee on talks to develop an ILBI on plastic pollution, including in the marine environment, delegates were unable to reach a consensus on the proposed treaty text (Global Plastic Action Partnership, 2022). More than 2 600 participants from 183 countries attended this meeting, with delegates committed to continuing the treaty drafting process. A list of key global initiatives designed to mitigate the growing problem of plastic pollution and the negative environmental impacts is available from Lacourt *et al.* (2024).

² <https://www.unep.org/environmentassembly/unea5>



Food safety personnel conduct quality checks at a fish packing plant.

CHAPTER 2

FOOD CHEMICAL SAFETY ISSUES RELATED TO FCMs

From a food safety perspective, FCMs and their constituents, including IAS and impurities, are typically subject to premarket controls. This involves conducting appropriate migration studies using defined food simulants to identify the specific migrants associated with the use of the FCM and to estimate dietary exposures. After identifying and quantifying exposure, any potential risk posed by the migrants is assessed by comparing it with available toxicological data. Following a successful assessment, the FCM can be added to a positive list of permitted substances for use in FCMs, typically specific to the intended use conditions and food matrix. If necessary, specific migration limits (SMLs) can be established in legislation for individual FCM chemicals, including any specific additives. While SMLs can be established for chemicals that have undergone a full risk assessment, the European Union (EU) has also set an overall migration limit (OML) of 60 mg/kg of food, which applies to the total or sum of all constituents released into food or food simulants (EC, 2011). For substances that are not classified as carcinogenic, mutagenic, or reprotoxic, and that are NIAS, the European Union set a separate migration threshold limit of 10 µg/kg. Exceeding this limit triggers the requirement for a more detailed toxicological evaluation as a condition of the overall assessment. Exposure thresholds have also been developed for structurally related classes of chemicals that may have limited toxicological data. This approach, known as the threshold of toxicological concern (TTC), is described in more detail in later sections.

Additional details on the legislative controls of FCMs currently in place in various countries – including the United States of America, Canada, Japan, China, and the European Union – are available from Aversano (2025) and Nerin *et al.* (2025). The overall purpose of FCM-related legislation is to ensure that materials and articles intended to come into direct or indirect contact with food provide a high level of protection of human health.

Although the CAC does not set specific standards for food packaging materials, it incorporates packaging requirements in most of its standards to safeguard food safety and quality. CAC standards provide guidance on packaging integrity and aseptic packaging conditions. This approach highlights the importance of FCMs



Bagged rice moves through an automated packaging facility.

and promotes the use of non-toxic food-grade materials (new or recycled) in food production.

Key examples of these provisions can be found in the *General Principles of Food Hygiene* (FAO and WHO, 2023a) and other codes of practice, such as the *Code of Hygienic Practice for Aseptically Processed and Packaged Low-Acid Foods* (FAO and WHO, 1993), as well as in commodity-specific standards such as those for fresh fruits and vegetables. Additionally, the *General Standard for Contaminants and Toxins in Food and Feed* (FAO and WHO, 1995) provides guideline levels for two specific chemicals – acrylonitrile and vinyl chloride monomer – and recommends minimizing their migration from FCMs into food to the lowest technologically achievable level.

It has long been recognized that food packaging materials are not completely inert and can release small quantities of their constituent chemicals into food and beverages through a process known as migration. Various studies on chemical migration have shown that hundreds of chemicals from FCMs can be found in foods, while thousands of chemicals can be extracted and identified from the FCMs themselves (Geueke *et al.*, 2025). For example, studies have shown that chemical substances used during the polymer synthesis of plastic food packaging can migrate throughout the product's life cycle, including during food use (Muzeza, Ngole-Jeme and Msagati, 2023; Gupta *et al.*, 2024). The matrix of plastic packaging materials

contains various chemical substances used during the manufacturing process, such as metals used as chemical reaction catalysts, solvents, monomers, and different reaction by-products (Panou and Karabagias, 2024). Various additives, such as plasticizers, stabilizers, and antioxidants, added to improve the functionality of plastic materials, can also migrate. It has been reported that more than 12 000 chemicals can be used intentionally during the manufacturing of various types of FCMs, often referred to as IAS (Groh *et al.*, 2021). UNEP has identified ten groups of chemicals found in plastics across a wide range of sectors and products, including FCMs, as being of major concern due to their known toxicity and potential for release from plastics. The list includes specific flame retardants, ultraviolet light stabilizers, per- and polyfluoroalkyl substances (PFAS), phthalates, bisphenols, certain alkylphenols and alkylphenol ethoxylates, biocides, metals and metalloids, polycyclic aromatic hydrocarbons (PAHs), and NIAS such as polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/Fs) (UNEP and Secretariat of the Basel, Rotterdam, and Stockholm Conventions 2023).

Additionally, many of the chemicals used in the manufacture of FCMs have been detected in humans through various biomonitoring studies (Muncke *et al.*, 2025). Based on a review of these studies, it was recently reported that there is evidence of human exposure to 3 601 food-contact chemicals (Geueke *et al.*, 2025). Generally, these IAS are low molecular weight chemicals that are either monomers of the starting materials or substances intentionally added to the FCM for a specific functional purpose. Many factors related to the type of packaging material and the food matrix – such as temperature, contact time, the chemical composition of the packaging material, the structure of the food, and the size of the contact surface between the packaging and the food – have been shown to influence the extent of migration (Kato and Conte-Junior, 2021). Additional details on the migration of chemicals from packaging materials into food can be found in several sources (Gupta *et al.*, 2024; Bronczyk *et al.*, 2025; Muzeza, Ngole-Jeme and Msagati, 2023; Seref and Cufaoglu, 2025; Zhang *et al.*, 2025).

The premarket evaluation of FCM chemicals – including starting monomers, reaction materials, and IAS – depends on the availability of comparative toxicological data. In order to address the large number of chemicals with limited hazard data potentially migrating into food in relatively small quantities, the concept of a TTC approach was developed originally from a review by Frawley (1967), based on analysis of the chronic toxicity data of chemicals in three structural classes identified according to a decision tree proposed by Cramer, Ford and Hall (1978). The TTC approach is based on the concept that reasonable assurance of safety can be provided even without chemical-specific toxicity data, as long as the intake is sufficiently low. This means an exposure level can be defined below which there is no significant risk to human health (Munro, Renwick and Danielewska-Nikiel, 2008). The TTC approach can support safety assessments for authorizing new substances, complementing the evaluation of primary toxicological data for these substances and their related impurities. In addition, TTC thresholds are useful for assessing potential contaminants in recycled plastics, especially when the identities of these contaminants are generally unknown and comprehensive screening for all possible

substances is impractical. Using this approach, the United States Food and Drug Administration (US FDA) established a dietary concentration limit of 0.5 ng/g of food for chemicals derived from FCMs, equivalent to exposure of 1.5 µg per person per day. This limit is referred to as a threshold of regulation (US FDA, 1995). For substances for which there are structural alerts for genotoxicity, but which are not aflatoxin-like, azoxy- or *N*-nitroso compounds, the US FDA considers using a more conservative threshold of 0.15 µg per person per day.

Limitations initially associated with the TTC approach were identified, particularly for genotoxic or bioaccumulative substances. In addition, the TTC approach does not account for cumulative or mixture effects, which may lead to an underestimation of the true risk posed by complex migrating NIAS chemical profiles (Miralles *et al.*, 2025).

Recently, the US FDA completed an update of the toxicological database that served as a foundation for their original TTC approach. The original database was greatly expanded to create an Expanded Decision Tree (EDT) that incorporates toxicity studies, metabolism data, and chemical structure information for a diverse range of chemicals. This expansion drew on reports published by independent expert scientific advisory bodies such as the Joint FAO/WHO Expert Committee on Food Additives (JECFA), the Joint FAO/WHO Meeting on Pesticide Residues (JMPR), and by bodies such as the United States Environmental Protection Agency (US EPA), the European Chemicals Agency (ECHA), and the European Food Safety Authority (EFSA). The revised EDT has identified three additional classes of chemicals (high, very high and extreme toxicity) and now includes a class VI, intended to cover the most toxic substances included in the database. Class VI chemicals have a revised TTC value of 0.00053 µg/kg bw per day, approximately one-fifth of the genotoxic carcinogenicity threshold of 0.15 µg/person per day (0.0025 µg/kg bw per day). The US FDA anticipates that the class VI TTC level will provide effective protection for all substances classified under EDT class VI.³

The TTC approach is a method of risk characterization that incorporates the extrapolation of toxicology data from studies of hundreds of diverse chemicals conducted over the past 50–60 years to substances with limited or no toxicological data, considering their predicted or known low levels of exposure. The TTC principle has been adopted and continuously updated by various food safety authorities, regulatory organizations and relevant scientific bodies, including JECFA and EFSA, and has been used to evaluate cosmetics, pharmaceutical intermediates, food flavouring agents, fragrances, and indirect food additives or FCMs. Detailed information on the development and application of the TTC, including chemicals excluded from its scope, can be found in Munro (1990), Munro *et al.* (1996), Kroes *et al.* (2004), and EFSA and WHO (2016). Where migrating substances have known chemical structures and can be classified within the TTC structural scheme, the approach offers a practical means of evaluating FCMs and prioritizing chemicals for further toxicological assessment.

³ https://www.fao.org/fao-who-codexalimentarius/sh-proxy/fr/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FMeetings%252FCX-702-86%252FWorking%2BDocuments%252Fex86_02_Add3e_rev2.pdf



A person fills a reused plastic bottle with drinking water at a public tap.

© FAO/Riccardo De Luca

2.1 FOOD SAFETY CONSIDERATIONS RELATED TO MICRO- AND NANOPLASTICS IN FCMs

The detection of micro- and nanoplastics from various sources in multiple human tissues and organs – including blood, breast milk, lungs, heart, and placenta – has confirmed human exposure (Leslie *et al.*, 2022; Ragusa *et al.*, 2021; Jenner *et al.*, 2022; Yang *et al.*, 2023). This implies translocation or absorption from the gastrointestinal tract (see [Box 3](#)). Compared to microplastics, nanoplastic particles are considered to be more reactive and more abundant in various environmental compartments. They can penetrate more easily into living cells, thereby possibly resulting in a higher toxicity (Sharma *et al.*, 2023; Ruggieri *et al.*, 2025). A recent review by researchers from the German Federal Institute for Risk Assessment (BfR) stated that currently, there is limited reliable information on the actual distribution of microplastics in humans. However, it is considered highly likely that orally ingested microplastics larger than 1.5 μm are not absorbed or distributed through the intestinal barrier (Janzik *et al.*, 2025). Even with limited bioavailability, ingested or absorbed microplastics have been associated with disruptions in the human gut microbiome, a phenomenon known as dysbiosis. The extent of this disruption depends on specific properties of microplastics, such as their type, size, and concentration (Thin *et al.*, 2025; Gao *et al.*, 2025).

A review of the types and physical characteristics of microplastics released from various food packaging materials is provided by Jadhav *et al.* (2021). Several recent reviews provide a list of common food items in which microplastics have been detected along with the concentration (Khatoon *et al.*, 2025; Gune and Martin, 2025;

Pathak, Mangla and Bhan, 2025; Duncan *et al.*, 2024). In addition, a recent study reported the combined concentration of micro- and nanoplastics in a variety of foods, along with estimated ingestion rates (particles per day) (Duda and Petka, 2025).

A recent review has reported that humans may ingest 39 000–52 000 microplastic particles annually, with bottled water consumers ingesting up to 90 000 more particles than tap water consumers (Sajedi, An and Chen, 2025). Although most bottled water is sold in plastic, a recent study in France found microplastics in beverages bottled in glass, sometimes at higher concentrations than similar beverages bottled in plastic (Chaïb *et al.*, 2025). The authors proposed that the source of the microplastics was from the plastic lids used with the glass bottles, although the detected microplastics may also have originated from the plastic FCMs used in the food production process (Muncke *et al.*, 2025). A study investigating the presence of nanoplastics in beverages reported no significant difference in the presence of nanoparticles found in cans, glass bottles, and plastic bottles across three similar carbonated soft drinks (Salvia *et al.*, 2025). While the World Health Organization (WHO) acknowledges that microplastic particles are present in food and drinking water, as of 2022, the available data were considered to have very limited value for assessing the risk of nanoplastics to human health (WHO, 2022). The Food and Agriculture Organization of the United Nations (FAO) also reviewed the available evidence on human exposure to micro- and nanoplastics, and stated that while there are concerns about potentially negative public health impacts from their chemical constituents and contaminants, the available evidence was too limited to conclude on the public health significance of such exposure (Garrido Gamarro and Costanzo, 2022a; 2022b).

One of the main challenges in assessing potential human health risks associated with exposure to micro- and nanoplastics is the lack of consistency in sampling methodology, analytical techniques, standard reference materials, and reporting units across studies, which makes it difficult to compare data (Alam and Rahman, 2025). Errors can occur at any stage of the microplastics quantification process, including in environmental sampling, sample processing, enumeration, and identification (McIlwraith *et al.*, 2025). EFSA, in a recent review of micro- and nanoplastic release from FCMs, indicated that based on a number of data gaps, including the lack of validated test protocols and suitable analytical methods, the actual extent of particle release is much lower than what has been reported in scientific publications (EFSA *et al.*, 2025). A recent meta-analysis of human studies associated with quantifying exposure to micro- and nanoplastics and associated health effects concluded that the current state of science warrants the development of strategies to reduce exposure to these particles to protect human health (Lamoree *et al.*, 2025). A variety of representative needs to inform policy and decision-making in the regulation of micro- and nanoplastics in food are available from Duncan *et al.* (2024).

BOX 3

STATUS OF RESEARCH ON THE IMPACT OF MICRO- AND NANOPLASTICS ON HUMAN HEALTH

Several recent reviews have highlighted the proposed connections between exposure to microplastics and a wide range of adverse human health effects (Li *et al.*, 2023, Li *et al.*, 2025; Luo *et al.*, 2025; Ezhava, Lobo and Rodge, 2025; Hoang *et al.*, 2025; Khu, Li, and Zhao, 2025; Nahaji *et al.*, 2025; Ali-Hassanzadeh *et al.*, 2025). However, these findings are primarily based on observational studies and do not establish causal relationships. Prior to fully understanding the potential health risks to humans from exposure to micro- and nanoplastics, several uncertainties must be resolved. These include analytical methods, exposure assessments, dose-response relationships, specific target organs, and the underlying toxicological mechanisms.

The primary routes of human exposure to microplastics are considered to be ingestion, inhalation, and to a lesser extent, dermal contact, with food, water, and air acting as the main carriers (Nouri, Massahi and Hossini, 2025). While food contact materials (FCMs) represent both a primary and secondary source of human exposure to micro- and nanoplastics, other exposure routes – such as environmental media and non-food items like textiles and consumer products – must also be considered in any comprehensive health risk assessment. Future risk management approaches will need to address evidence from a recent meta-analysis indicating that more than 96 percent of FCMs release both microplastics and nanoplastics during normal, intended use (Zimmermann *et al.*, 2025).

2.2 NANOMATERIALS IN FOOD PACKAGING

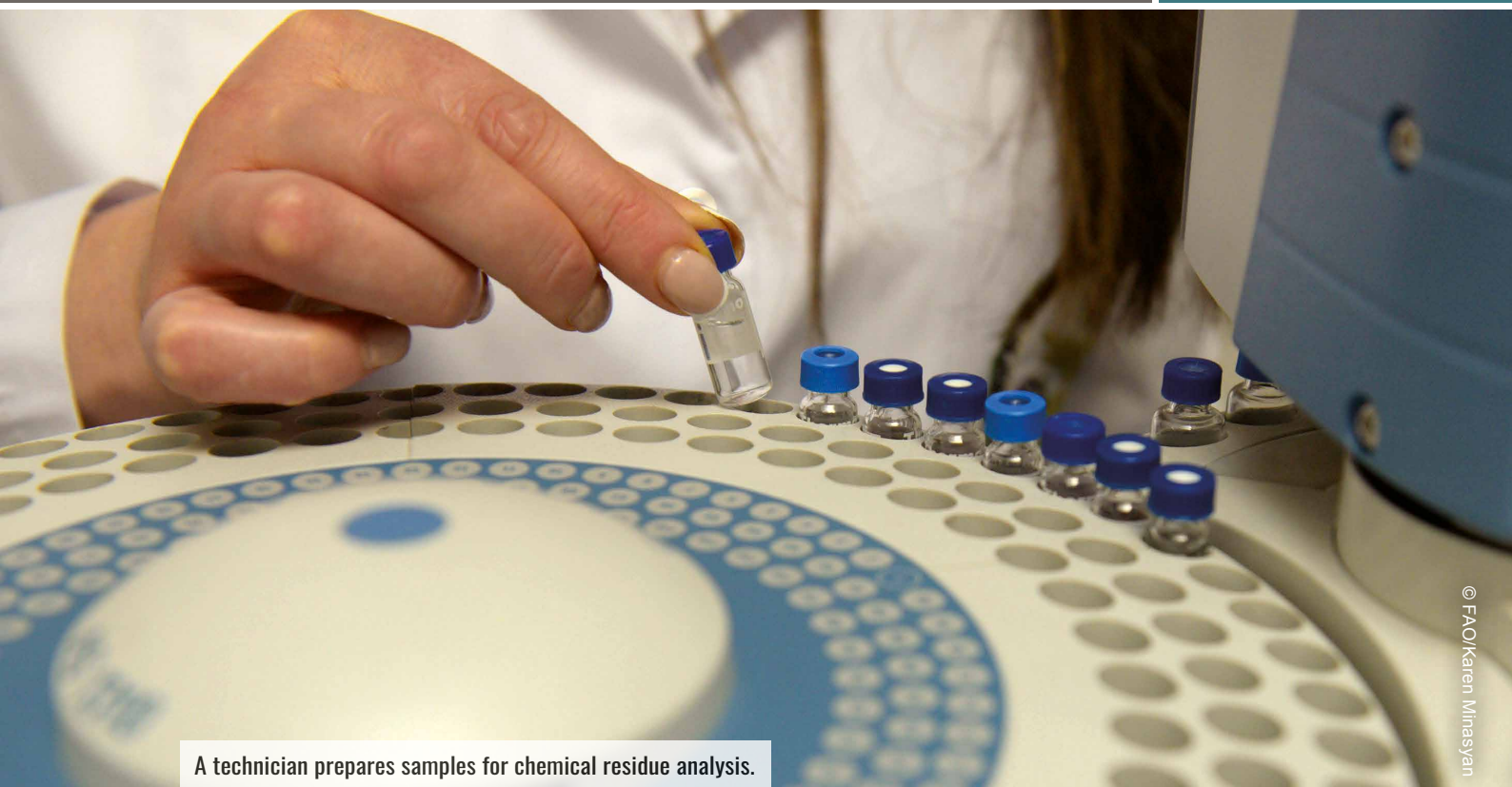
Nanomaterials (at least one dimension in the size range of 1–100 nm) are increasingly being explored for their use in food packaging. Nanomaterials can be incorporated into packaging polymers to improve key physical and mechanical performance characteristics – such as strength, durability, flexibility, barrier function, and overall service life (Ashfaq *et al.*, 2022). In particular, nanoparticles used in FCMs, including silver, zinc, copper, and titanium oxides, have been reported to boost mechanical and barrier performance while also helping to limit oxidation and spoilage and impart antimicrobial activity (Cano *et al.*, 2016; Lin *et al.*, 2015; Cao *et al.*, 2018; Ren *et al.*, 2015).

Nanomaterials are also increasingly being developed for use in active packaging, which is designed to facilitate interactions between food and packaging materials to maintain or extend the shelf life of food products while ensuring their quality, safety, and integrity (Mahmud *et al.*, 2022; Peng *et al.*, 2024; Singh *et al.*, 2025; Panigrahy and Rout, 2025).

As global efforts to reduce synthetic plastics and increase the use of recycled and environmentally friendly biomaterials in food packaging grow, incorporating nanomaterials into the packaging material matrix has shown promise in enhancing functionalities such as gas and moisture barrier properties and mechanical strength (Gupta, Guha and Srivastav, 2024).

Nanomaterials used in active packaging, particularly those with antimicrobial properties, would be considered an IAS for which a standard premarket safety assessment would be required prior to use. Various metal oxides that can be used as part of active packaging have been shown to migrate into food, which would necessitate an exposure assessment and hazard characterization (Vats, Arora and Tiwari, 2024). For instance, if nano forms of any metal oxides are used in a FCM, migration assessments would need to consider the nano form itself and the possible migration and whether a nano-specific toxicological assessment is required. For instance, limited migration has been demonstrated for zinc oxide nanoparticles used as part of active packaging, and therefore the safety evaluation focused on the migration of soluble ionic zinc only rather than on the nanoparticle form (EFSA CEF Panel, 2016). While various types of nanoparticles, nanocomposites, and nanosensors can be used in food packaging, accurate characterization of any potentially migrating nanoparticles into food would be required.

From a toxicological perspective, nanomaterials can show different and unique toxicological properties compared to their non-nano counterparts due to factors such as size, shape and aspect ratio (ratio of length to width, or diameter, of a particle), surface chemistry and aggregation (Naseer *et al.*, 2018; Bharti, Pal and Kumar, 2025). In recognition of the unique toxicological properties of nanomaterials, several national and international food regulatory agencies have developed specific policies to regulate their use. For example, Commission Regulation (EU) No. 10/2011 on plastic materials and articles intended to come into contact with food includes provisions specific to nanomaterials, requiring that any nanomaterial used in food-contact applications undergo a risk assessment before approval (Störmer *et al.*, 2017). In the United States, the US FDA requires manufacturers to submit data specific to the potential migration of nanomaterials into food and toxicological effects to demonstrate the safety of nanomaterials used in FCMs. The US FDA has also issued guidance documents to assist industry stakeholders in assessing the safety of nanomaterials (US FDA, 2018). In Canada, products that come into contact with food are regulated under the Food and Drug Regulations, with additional guidance provided for the use of nanomaterials (Health Canada, 2022). Although many countries have made progress in regulating nanomaterials, global alignment and consistency remain a major challenge due to differences in risk thresholds, regulatory definitions, and reporting requirements. A review of available regulations currently in place in different countries for the use of nanoparticles/nanomaterials in the food and agriculture industries is available from Jangid *et al.* (2025).



A technician prepares samples for chemical residue analysis.

© FAO/Karen Minasyan

2.3 INTELLIGENT FCMs

In addition to active FCMs, intelligent food packaging has been developed to monitor the quality and safety of food products. It provides real-time information to manufacturers, retailers, or consumers related to changes in measured parameters via sensors or indicators integrated into the packaging (Vanderroost *et al.*, 2014). Various parameters that can be monitored using intelligent packaging include time-temperature indicators, freshness indicators, packaging integrity indicators, biosensors, and gas sensors (Mkhari, Adeyemi and Fawole, 2025; Roy *et al.*, 2023). According to the EU legal definition (EC, 2009), intelligent packaging contains a component that enables the monitoring of the condition of packaged food or the environment surrounding the food during transport and storage. Specific examples of various types of intelligent food packaging, along with recent technological innovations, can be found in literature by Kumar *et al.* (2025), Mkhari, Adeyemi and Fawole (2025), and Roy *et al.* (2023). Sensing molecules can be incorporated either directly into the primary packaging material or applied as a coating on the surface of the packaging materials, allowing direct contact between the sensing molecules and the food products (Hu and Li, 2024). New developments in food packaging combine elements of both active and intelligent packaging materials into a single system. However, any chemicals used to produce intelligent FCMs must take into account the potential migration of the unique IAS and the need for a specific safety assessment for those compounds. For example, a food packaging material

has been developed that combines the antimicrobial properties of zinc oxide with a pH-sensitive film containing anthocyanin (Koshy *et al.*, 2023). Both zinc oxide and anthocyanin qualify as IAS; however, any migration of these substances must be evaluated during the chemical safety assessment process. For example, in the United States, components of intelligent food packaging materials are subject to the same US FDA requirements as all other food-contact substances (Lacourt *et al.*, 2024). However, several impediments to the large-scale use of intelligent food packaging exist, including the substantial costs associated with production and technical complexities. These have been identified as significant barriers to the widespread use of intelligent FCMs in the food industry (Mkhari, Adeyemi and Fawole, 2025). The authors of this report argue that any substances used as components of active and/or intelligent FCMs intended to come into direct contact with food or be released into it must be thoroughly evaluated, just like other IAS used in food packaging, before they are used in a marketed product.

2.4 RECYCLED PLASTICS AND FOOD SAFETY CONSIDERATIONS

Numerous initiatives to reduce plastic waste are being successfully implemented worldwide. An important aspect of implementing a circular economy for food packaging materials is creating a system which recaptures or recycles plastic waste to manufacture new materials and products. In the EU, the 2020 Circular Economy Action Plan includes key measures to encourage the design of FCMs that are easy to recycle, as well as initiatives to promote refillable and reusable FCMs (EC, 2020). According to Regulation (EU) 2025/40, packaging should be “designed, manufactured and commercialized in such a way as to allow for its reuse as many times as possible or for high-quality recycling, and to minimize its impact on the environment during its entire life cycle and the life cycle of the products for which it was designed” (EC, 2025a). By 2030, Japan’s Plastic Resource Circulation Strategy targets three outcomes: reusing or recycling 60 percent of all plastic containers and packaging, slashing single-use plastic emissions by one-fourth, and starting to introduce bioplastics. By 2035, Japan aims to effectively utilize all plastic waste by reuse, recycling, and other recovery (including energy recovery) (Government of Japan, 2019). While some global estimates show that recycling rates for certain plastics can be relatively high (17 percent for PET), other synthetic polymers used in FCMs, including high density polyethylene (HDPE), low density polyethylene (LDPE), PVC and PP, have recovery rates of less than 10 percent (Merrington, 2024). The Organisation for Economic Co-operation and Development (OECD) has estimated that the use of recycling as a means to curb plastics pollution would require recycling rates (material actually reprocessed into new products) of 60 percent by 2060 (OECD, 2022). However, it is recognized that there are several challenges to achieving even modest recycling rates, including material complexity, polymer degradation, chemical contamination, and possible production of microplastics (Carney Almroth *et al.*, 2025).

BOX 4

MECHANICAL AND CHEMICAL RECYCLING USED FOR PLASTIC FOOD CONTACT MATERIALS

The principal recycling processes used for plastic food contact materials (FCMs) involve primary, secondary, and tertiary recycling. Primary recycling uses scraps generated during the production of food-contact plastics in a good manufacturing practice environment and reprocessing them within a closed-loop system into FCMs. Secondary or mechanical recycling involves grinding, melting, extrusion, and other physical methods to produce FCMs from post-consumer waste feedstock. This process removes residual contaminants from the feedstock while ensuring that the polymer composition and structure of the reprocessed plastics remain unchanged. Tertiary or chemical recycling refers to a process that involves chemically decomposing recycled post-consumer feedstock materials into original monomers or oligomers, followed by refining, distillation, and purification to remove residual contaminants. The purified monomers are then repolymerized through chemical reactions to produce new plastic pellets. Part of the submission process for applications involving mechanical and chemical recycling requires evidence related to the surrogate contaminant testing report or to verify that the recycling process has demonstrated sufficient decontamination capability. In general, mechanical recycling is cheaper and less energy-dependent, but it can yield lower-quality polymers. Chemical recycling, by contrast, is better at separating mixed plastic waste materials into chemical components and can produce materials comparable to virgin plastics.

From a chemical safety perspective, the use of recycled plastics can present unique challenges (FAO, 2024). More than 16 000 chemicals identified as either intentionally used in plastic production or unintentionally present in plastics. Of these, over 4 200 chemicals have been identified as having various hazardous properties (persistent, bioaccumulative, mobile or toxic) (Monclús *et al.*, 2025; Wagner *et al.*, 2024), highlighting the importance of control over the waste stream to ensure non-food use plastics have been separated from food-use plastics prior to recycling. For example, experimental evidence shows that recycled PET and other plastics can contain both chemicals originally used in the primary materials and additional contaminants likely introduced during use, handling, processing, consumer misuse, environmental exposure or recycling (Geueke *et al.*, 2023; Carmona *et al.*, 2023). These chemicals can include a wide range of NIAS such as pesticides, pharmaceuticals and biocides, which would exclude their use in virgin FCMs. In a study comparing recycled plastics across product categories, including FCMs, with virgin plastics, the recycled plastics were found to contain elevated concentrations of various organic and inorganic chemicals, including metal(oids), PFAS and PAHs (Daggubati *et al.*, 2025). The authors also reported significant compositional differences between the functional categories of chemicals found in recycled and virgin plastics. These differences are likely due to various factors, including the use of different additives, variations in feedstock sources, degradation by-products and/or manufacturing residues present in the recycled plastics. Prior misuse of refillable PET bottles, such as storage of alcohol, cleaning products, and fuels, was identified as a potential source for organoleptic impacts in mineral water and soft drinks (Widén, Leufvén and Nielsen, 2005).



Vegetables grow in reused tires and repurposed plastic containers.

Additionally, cross-contamination during waste collection, particularly when separation at source is inadequate, has been suggested as a source of contamination in recycled PET (EFSA CEP Panel, 2024), although evidence remains limited. A greater concern is that unsafe storage of hazardous chemicals in reusable or refillable containers could lead to toxicity if the containers are not adequately decontaminated. Microplastics which had been produced from post-consumer recycled plastics of PP, LDPE and HDPE via a mechanical recycling process released more organic compounds and inorganic elements than microplastics milled from virgin plastics. In addition, extracted microplastics decreased human colorectal adenocarcinoma cell viability in a dose-dependent manner, with the observed effect more prominent with the recycled microplastics compared to their virgin counterparts (Järvelä *et al.*, 2025).

In general, recycled plastics that are evaluated and approved for food use should be determined safe for food use, consistent with the use of virgin FCMs. In the EU, Commission Regulation (EU) 2022/1616 establishes rules to ensure recycled materials meet the same safety and quality standards as virgin plastic. Only suitable, authorized recycling processes, such as post-consumer mechanical PET recycling, are permitted (EC, 2022). This regulation sets requirements for producing plastics with recycled content that do not pose risks to consumer health or compromise food safety, with the EFSA responsible for verifying that recycling processes effectively reduce plastic contamination levels. For substances which have not previously undergone a risk assessment, Commission Regulation (EU) 2025/351 defines a migration threshold of 0.15 ng/g, where no risk assessment is required. For substances migrating at concentrations greater than 0.15 ng/g,

but less than 50 ng/g, the risk assessment is limited to excluding genotoxicity (EC, 2025b); if above 50 ng/g, a full risk assessment in accordance with international standards is needed. A more complete review of regulatory frameworks in the European Union regarding recycled plastics intended for food contact is available from Sepúlveda-Carter *et al.* (2025). While the US FDA has not yet promulgated any regulatory requirements pertaining to the use of recycled materials in food-contact applications, the Agency has issued a guidance document (US FDA, 2021) that describes methods to be used to ensure that the finished, recycled material is suitably pure for the intended use. Since 1990, the US FDA has issued opinions for at least 423 manufacturer applications on whether the subject recycling process is expected to produce recycled materials suitable for food-contact applications (EHN, 2024). In the United States, it is the manufacturers' responsibility to ensure that a recycling process is sufficient to reduce any contaminants below the dietary concentration threshold of 0.5 ng/g or 1.5 µg per person per day.

This dietary concentration threshold is derived from the US FDA's threshold for regulating substances used in food-contact articles. The threshold exempts from regulation substances whose use in food-contact articles results in a dietary concentration of 0.5 ppb or less. The upper-bound lifetime cancer risk from use of a substance migrating at 0.5 ppb or less is expected to be below one in a million. This risk level is generally regarded as very low (i.e. posing negligible safety concerns) (Federal Register, 1995).

WHO and EFSA have proposed an exposure threshold of 0.0025 µg/kg bw per day (expected to present less than a one in a million [1×10^{-6}] upper-bound lifetime risk of cancer) as sufficiently protective for DNA-reactive genotoxic chemicals (EFSA and WHO, 2016; EFSA *et al.*, 2019). This threshold is also considered applicable to unknown contaminants or NIAS that may have been present in the plastic feedstock but were effectively removed through a cleaning process (EFSA CEF Panel, 2016).

As part of assessing how to effectively remove incidental contaminants from waste plastic feedstock, a challenge test has been developed and is used by a variety of regulatory agencies, including the US FDA, EFSA, Health Canada and the Brazil National Health Surveillance Agency, as part of the recycled plastics approval processes. This test employs a wide variety of representative chemical contaminants (polar volatile, non-polar volatile, polar semi-volatile, non-polar semi-volatile, and metal salt) that are used to intentionally contaminate plastic waste feedstock. The intentionally contaminated materials are then subject to both a cleaning process and to standard migration tests with food simulants to demonstrate the ability of the recycling process to remove unapproved additives and potential contaminants from plastics originating from both food- and non-food use (Tumu, Vorst and Curtzwiler, 2024). In the US FDA guidance document, details on how surrogate contaminant testing can be conducted are provided, including the Agency's current recommendations for the choice of chemical surrogates. In addition, the Commission Regulation (EU) 2022/1616 established specific requirements and procedures for collecting and pre-processing plastic waste, decontamination procedures, and quality control of recycled plastics to ensure that plastics intended for food contact are both chemically and microbiologically safe (EC, 2022).



A worker fills plastic containers with soybean oil for storage at a processing facility.

A similar process for determining the safety of recycled plastics is used in Brazil. Brazil's Technical Report No. 71/2016 (TR71/2016), published by the National Health Surveillance Agency, addresses the presence of contaminants in recycled plastic materials intended for food contact (Brazil, 2016). Any recycled plastics intended for use as a FCM must provide documentation demonstrating that the recycled material meets all existing legislation for food plastics (Marcelino, Gomes and Marangoni Júnior, 2025). To assess the effectiveness of the cleaning process, a polymer-specific challenge test is required, in which surrogate contaminants spanning a wide range of physicochemical properties are added to the feedstock to ensure any chemical migration to food simulants is within the established limits. In Brazil, these surrogates have a limit of 220 ng/g for food-grade post-consumer recycled PET, based on the maximum allowed (regulatory threshold) in the human diet, which is 0.5 ng/g of food (Brazil, 2008).

In Canada, FCMs safety is described in regulations as a general prohibition on the sale of foods in packages that may impart any substance to the contents which may be harmful to the consumer of the food. Currently, Canada employs a voluntary submission system and guidance documents are provided detailing how a manufacturer or seller of FCMs can apply for a premarket safety assessment. As part of Canada's environmental initiative of a Strategy on Zero-Plastic waste, with a goal of zero plastic waste by 2030 (CCME, 2019), updated guidelines are also provided by Health Canada to assist recyclers, manufacturers and sellers in determining the safety and acceptability of post-consumer recycled plastics for food packaging. Part of the process for determining the efficiency of removing contaminants from post-consumer plastic feedstock involves using a challenge test with surrogate chemical contaminants. Following this challenge test, the health significance of any potential chemical exposure is assessed by comparison to a threshold of concern (TOC) value of 25 ng/kg bw per day, which represents an exposure below which a substance is unlikely to pose a risk via food packaging (Health Canada, 2023).

Another option for ensuring the safety of recycled plastics used as FCMs is to implement a functional barrier design, in which the recycled plastic is covered on the food-contact surface with a virgin plastic polymer to limit or prevent chemical migration.

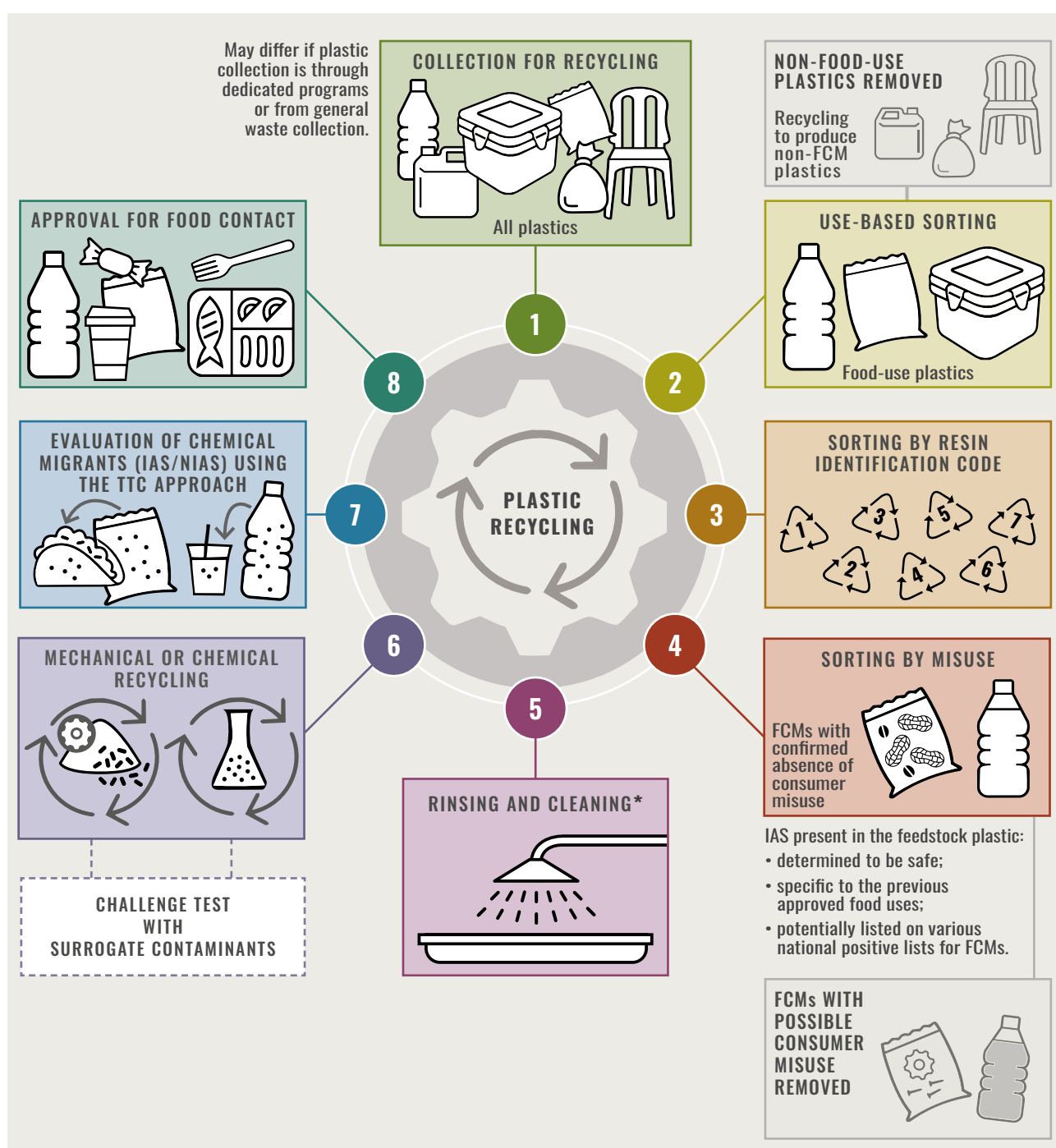
Using recycled plastics as FCMs presents chemical food safety challenges, in particular for substances classified as NIAS. The TTC concept provides a realistic and pragmatic approach for both migrating chemicals with known structural similarities to the TTC-defined chemical classes and for unknown chemicals with limited or no hazard data.

2.4.1 RECOMMENDATIONS FOR ENSURING FOOD SAFETY OF RECYCLED FCMs

With suitable waste stream control and sorting systems, food-use plastic packaging materials can be separated before recycling according to synthetic polymer-specific Resin Identification Codes (see [Figure 1](#)). For food packaging that has not been used for non-food purposes or misused by consumers, any IAS present in the feedstock plastic should already have been evaluated and deemed safe for its previously approved food uses, and potentially be listed on national positive lists for FCMs. For example, after a 5-year transition period ending 1 June 2025, Japan has recently established a rule under their Food Sanitation Act that any synthetic resin (polymers and additives) used in FCMs sold in Japan must appear on an official positive list. Substances not on the positive list can be used out of scope, provided they meet certain conditions, such as being used in non-contact layers with migration levels into food below 0.01 µg/g (CAA, 2025). A number of other nations and regions, such as the United States, Canada and the European Union, have also established similar positive lists where approved polymers and additives can be confirmed and compared to any SML.

Where waste disposal or recycling facilities cannot ensure adequate separation of food-use and non-food use polymers, or confirm that plastic containers were not misused, dedicated cleaning steps with positive control chemical surrogates can be implemented to ensure adequate removal of NIAS and contaminants. Commission Regulation (EU)10/2011 defines that “non-intentionally added substance means an impurity in the substances used or a reaction intermediate formed during the production process or a decomposition or reaction product” (EU, 2011). Canada considers NIAS as chemicals that may be present as side products formed during manufacture, breakdown products, and contaminants, including contaminants resulting from recycling (ECCC and Health Canada, 2025). NIAS with known chemical structures can be assessed against migration or intake limits using available decision trees and the TTC approach used by regulatory agencies. For unknown NIAS, a conservative approach can be applied: assign the most conservative chemical class and compare any potential exposure with the most conservative TTC value, which would consider possible structural alerts for genotoxicity. Alternatively, default migration limits can be assigned to NIAS which would account for all population exposure scenarios. Examples of analytical methods used for detecting NIAS in food packaging materials (Nerín *et al.*, 2022; Miralles *et al.*, 2025) and NIAS that have been detected in recycled plastics is provided by Pearson *et al.* (2024) and Rung *et al.* (2023).

FIGURE 1. STEPS OF PLASTIC RECYCLING FOR FOOD CONTACT MATERIALS – FOOD SAFETY CONSIDERATIONS



* Rinsing and cleaning can include multiple steps depending on the quality of the input material.

Note: Mechanical and chemical recycling can be applied as alternative steps within the overall plastic recycling process. More details are provided in Box 4. The challenge test is typically required as an initial validation of the recycling process and is repeated when significant changes occur, e.g. when setting process parameters or configuring equipment.

FCMs: food contact materials
IAS: intentionally added substances
NIAS: non-intentionally added substances
TTC: threshold of toxicological concern

Source: Authors' own elaboration.



Stacked plastic deli tubs filled with marinated olives.

© FAO/David Blacker

2.5 ALTERNATIVE MATERIALS FOR FOOD PACKAGING

Under the circular economy approach, the “redesign-reduce-reuse-recycle” principles guide efforts to make synthetic plastic food packaging more sustainable. Complementing these strategies, developing food packaging from biodegradable materials with functionalities comparable to conventional petroleum-based, non-biodegradable plastics can further help address environmental concerns (FAO, 2022). Compared with synthetic polymer-based FCMs, bio-based plastics provide advantages of possible carbon neutrality, although they are not necessarily biodegradable. Transitioning to bioplastics is estimated to help achieve a potential 13 percent reduction in carbon dioxide (CO₂) emissions in the EU, if the European Plastics Strategy (EC, 2018) targets for 2025 are met (Tenhunen-Lunkka *et al.*, 2023).

Some of the main materials used in the production of bioplastic FCMs derived from renewable resources include starch, cellulose, chitosan, hemicellulose, lignin, lipids and proteins, including blends of these materials (Figure 2). Further details on materials that can be used to produce bio-based FCMs are available from Teixeira-Costa and Andrade (2022); Pawde *et al.* (2025); Jahangiri, Mohanty and Misra (2024) and Hussain, Akhter and Maktedar (2024). Advantages and disadvantages associated with the manufacture and use of bioplastics are described in Huang *et al.* (2025). Bio-based food packaging polymers can also be produced from plant oils (palm seed, soybean, and linseed oil) or from fermentation-derived renewable materials including polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and polyhydroxybutyrates (PHBs).

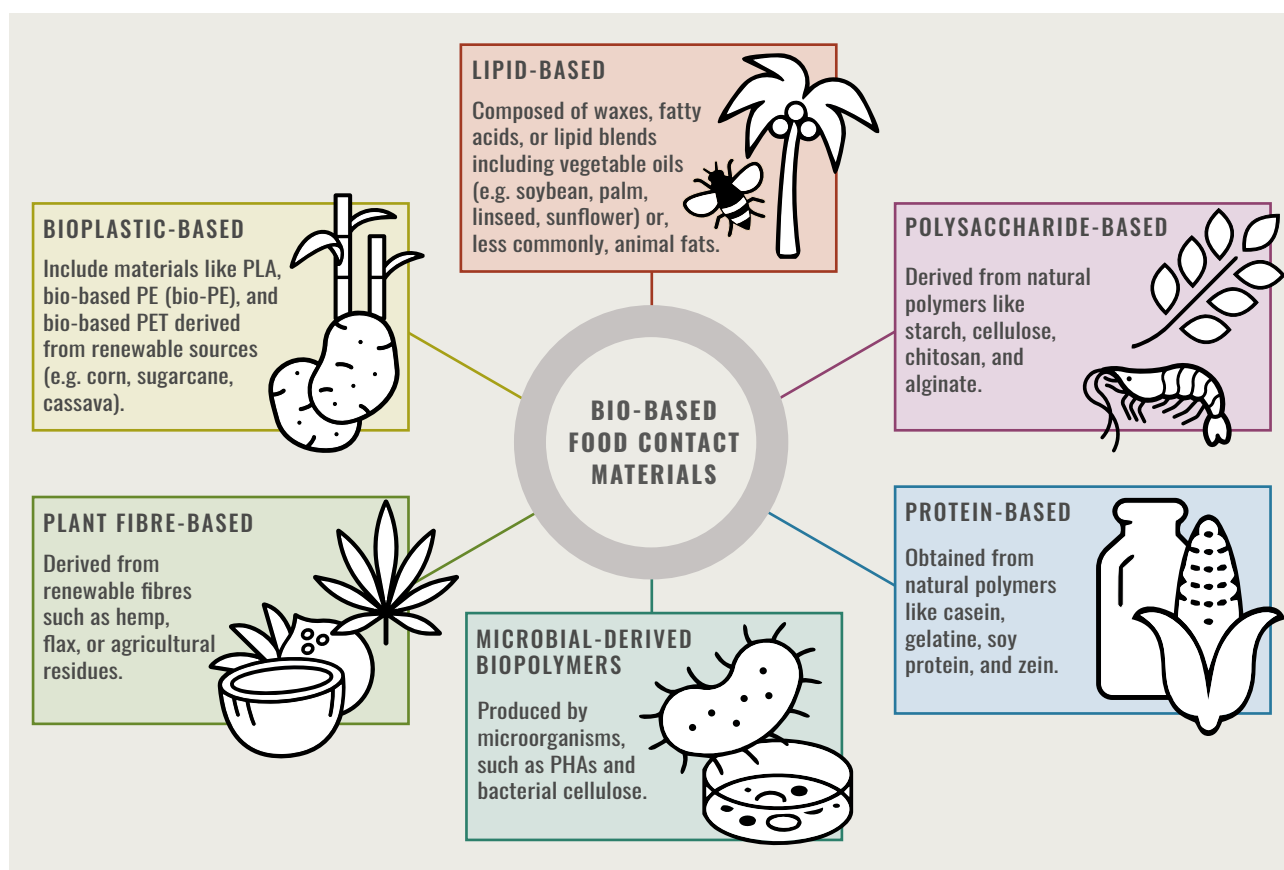
However, the polymerization of monomers from a renewable resource can produce polymers that, while chemically identical to traditional polymers, are not necessarily biodegradable. For example, sugarcane, corn, and cassava can be used to produce bio-based PE, bio-based PP, bio-based PET, and bio-based polyamides (PAs) that have similar chemical structures and characteristics to their petroleum-based non-renewable counterparts but are not considered biodegradable (Harnkarnsujarit *et al.*, 2021). Examples of bioplastics that are both bio-based and biodegradable include PLA, PHAs and bio-based polybutylene succinate (Rosenboom, Langer and Traverso, 2022). Bioplastics can be categorized based on the raw material (renewable, fossil) from which they are produced, and on their biodegradability (Weinrich and Herbes, 2023). Additional details on bio-based materials being developed and used for food packaging are provided in Versino *et al.* (2023) and Shi *et al.* (2025).

Natural plant fibre-based FCMs manufactured from materials such as bamboo, straw, sugarcane pulp, and coffee grounds can partially replace the use of petroleum-based plastics. Natural plant fibres containing cellulose, hemicellulose and lignin have been widely used as raw materials in the production of FCMs (Vinod *et al.*, 2020). However, a large number of both IAS and NIAS have been detected either from migration studies or by extraction from natural plant fibre-based FCMs (Tang *et al.*, 2024). In a study on plant-based FCMs collected on the Dutch market, a gas chromatography-mass spectrometry screening revealed the presence of plant extractable plasticizers, antioxidants, hydrocarbons and various metals, including lead and mercury (Bouma *et al.*, 2024).

Protein-based packaging materials, such as casein, collagen, soy and gluten, are increasing in popularity, as they are produced from abundant renewable materials, inexpensive, non-ecotoxic, biodegradable, and have very good film-forming properties (Zubair and Ullah, 2020; Mihalca *et al.*, 2021). However, because many plant and animal proteins are food allergens, evaluating the potential migration of allergenic proteins is a distinct safety concern for FCMs and should be considered during safety assessments. For example, in a small survey of biodegradable FCMs, gluten was detected both in the finished FCMs and in migration studies with food simulants (Mossburger and Scherf, 2024).

Additional food chemical safety considerations will need to be addressed when developing bio-based plastics used in food packaging. NIAS unique to renewable biomaterials may include pesticides, natural toxins, allergens and environmental contaminants present in the biomass feedstock. For example, the US FDA recently issued an alert to Industry and Consumers about dinnerware manufactured from palm leaf, noting that naturally occurring toxins in these products can migrate to food at levels that may pose a health risk to consumers (US FDA Human Foods Program, 2025). Depending on the type of bioplastic, additional additives, or IAS, may be required to improve their functional properties, and their potential migration will need to be considered from a food safety perspective (Lacourt *et al.*, 2024).

FIGURE 2. THE MAIN SOURCES FOR BIO-BASED FOOD CONTACT MATERIALS



Note: Potential chemical hazards common to various types of bio-based materials used for FCMs include pesticide residues from agricultural feedstock; natural toxins (e.g. mycotoxins) from contaminated plant sources or naturally produced by plants; phytoestrogens, environmental and industrial pollutants such as persistent organic pollutants (POPs), dioxins, polychlorinated biphenyls (PCBs) and heavy metals; impurities and degradation products from processing. Other non-intentionally added substances (NIAS) are more specific to some types of materials, such as allergens originating from the feedstock of polysaccharide-based and protein-based FCMs (e.g. chitin, gluten, casein, soy proteins); oxidation products from lipid degradation (e.g. aldehydes, ketones) and hydrophobic contaminants like phthalates that can be absorbed by lipid layers in lipid-based materials; residual fermentation media (nutrients, salts, or antibiotics) from microbial growth in microbial-derived biopolymers, and by-products from microbial metabolism or polymer synthesis.

PE: polyethylene
 PET: polyethylene terephthalate
 PHAs: polyhydroxyalkanoates
 PLA: polylactic acid

Source: Authors' own elaboration.

While earlier work reported no data on migration of pesticides or natural toxins from bio-based plastics into food (Bonwick *et al.*, 2019), more recent research detected a wide range of potential migrant compounds, both volatile and semi-volatile, in commercial FCM samples labelled as bio-based and/or biodegradable (López Sanvicente *et al.*, 2025). A recent meta-analysis reported that many diverse chemicals can migrate into food or food simulants from bio-based and/or biodegradable FCMs (Lestido-Cardama *et al.*, 2025). As bio-based plastics continue to develop, their novel formulations may lack sufficient toxicological data and standardized testing protocols to ensure long-term safety (Leal Filho *et al.*, 2025).

CHAPTER 3

CONSIDERATIONS OF THE CODEX ALIMENTARIUS COMMISSION FOR FCMs

Discussions in the Codex Alimentarius Commission

At its Eighty-fifth Session, the Executive Committee of the Codex Alimentarius Commission (CCEXEC) (FAO and WHO, 2023b) agreed to recommend that the Forty-sixth Session of the Commission request the Codex Secretariat to issue Circular Letter 2024/20-CAC⁴ to Codex Members and Observers to “gauge whether there was interest, value, or need for new work on guidance from the CAC on food safety considerations related to the use of recycled material in food packaging” (FAO and WHO, 2023c). Following consideration of comments received in response to Circular Letter CX/EXEC 24/86/2 Add.3 Rev 2⁵, CCEXEC at its Eighty-sixth Session (FAO and WHO, 2024) noted Members’ and Observers’ interest in considering new work in this area and encouraged interested Member Countries to prepare a clear and complete proposal for new work. At the Eighteenth Session of the Codex Committee on Contaminants in Foods (CCCF) (FAO and WHO, 2025), it was agreed that a discussion paper on developing guidance related to food safety aspects of recycled plastics in food packaging would be prepared for consideration by the CCCF at its Nineteenth Session in 2026.

⁴ https://www.fao.org/fao-who-codexalimentarius/sh-proxy/hu/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FCircular%2520Letters%252FCL%2525202024-20%252Fcl24_20e.pdf&utm

⁵ https://www.fao.org/fao-who-codexalimentarius/sh-proxy/fr/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FMeetings%252FCX-702-86%252FWorking%252BDocuments%252Fex86_02_Add3e_rev2.pdf

*Some reflections based on the ongoing discussion of FCMs
in the Codex Alimentarius Commission*

The CCCF developed *Guidelines for Rapid Risk Analysis Following Instances of Detection of Contaminants in Food where there is No Regulatory Level* (FAO and WHO, 2019), which may or may not be applicable to any IAS or NIAS migrating from FCMs into food. While the Codex guidelines provide an approach to accommodate situations where there is limited or no toxicological data available for the chemical(s) in question through a TTC approach, any existing FCM regulatory frameworks may impact their application.

Increased attention to the use of FCMs manufactured from recycled plastics and alternative non-synthetic materials at the Codex level would help foster regulatory harmonization and provide international guidance to support countries in addressing these challenges.



Opening of the 46th Session of the Codex Alimentarius Commission.

CHAPTER 4

CONCLUSIONS AND WAY FORWARD

While there are many significant benefits to the use of recycled FCMs and the development of non-synthetic alternatives, this report highlights a series of critical food safety issues that must be addressed.

Applying circular economy principles to FCMs is essential for the transition of agrifood systems towards more sustainable solutions, but presents challenges related to recycling processes

The low cost of virgin polymer production, limited recycling capacity, poor waste management practices and persistence of substances in the environment have all contributed to the global plastic pollution epidemic. Extending the principles of a circular economy to FCMs would support more sustainable and efficient use of natural resources and enable material recovery and recycling at the end of a product's life. However, promoting post-consumer reuse of FCMs that were not originally designed based on circular economy principles creates challenges for implementing effective recycling strategies.

Ensuring the safety of recycled and bio-based FCMs requires addressing complex chemical risks, including contamination, unknown substances, and emerging human health concerns like micro- and nanoplastics

Even when FCMs are designed to facilitate recycling, specific chemical safety issues related to repeated food use (absorption of aroma compounds, flavours, and ingredients from food products into packaging materials) still need to be addressed before the recycled products could be reintroduced to the market. These include possible consumer misuse of FCMs for non-food purposes, post-consumer use contamination of plastics prior to collection and delivery to recycling facilities, identification of IAS used in the original FCM, and assessment of potential NIAS which could be transferred to the final recycled plastic. Additional chemical safety issues specific to the use of renewable materials in bioplastics production would also need to be addressed before food use. Although exposure to micro- and nanoplastics is not unique to recycled FCMs, this source of exposure would also need to be considered when developing strategies designed to reduce human exposure and mitigate potential human health effects.



Produce on display at a grocery store.

Closing data gaps on contaminants, designing exposure scenarios, and developing traceability systems is essential for advancing risk assessment of recycled FCMs

Toxicological data for some substances used in FCMs, in particular for NIAS, can be limited or inconsistent; more studies are needed to clarify hazard profiles and establish thresholds for NIAS and recycled FCM contaminants. Further development and refinement of validated, fit-for-purpose analytical tools for identifying IAS and NIAS in migration studies are needed to improve acceptance of recycled plastics. Further development of reference databases to support NIAS chemical structures identification would help ensure that compounds restricted under current regulations are not migrating into food. Additional research is also needed to supplement limited data on the occurrence, migration and health impacts of micro- and nanoplastics, specifically in relation to recycling and plastic alternatives. However, this field is rapidly evolving, and significant data gaps remain on possible food-safety implications. For micro- and nanoplastics, robust analytical methodologies for both quantification and particle identification will be crucial to advance food safety risk assessment and support the development of effective risk management strategies for these materials. Developing traceability systems and contaminant fingerprinting techniques may also help identify contamination sources in recycling streams.

Developing an inventory or a positive list of chemicals approved for use in the manufacture of FCMs, categorized by product type (resin codes), would support international understanding and recognition of intentionally used chemicals that have undergone a safety evaluation. Descriptions of the available databases specific to FCMs is available from Wiesinger *et al.* (2024).

This inventory would also help identify substances likely to be present in plastic waste streams feeding recycling FCM processes and flag products in those waste streams that may be problematic for recycling.

Updating and revising existing regulatory frameworks will provide a basis to ensure safe production and application of recycled FCMs

Current regulations, designed to assess the chemical safety of recycled plastics through rigorous cleaning and decontamination processes, and the application of the TTC approach to both IAS and NIAS residues offer a pragmatic solution to ensuring the safety of recycled FCMs. The TTC approach can be used for an initial assessment of a substance to determine whether a full risk assessment is required, and, more importantly, to define exposure levels below which human health risk is considered low even when full toxicity data are unavailable. The integration of New Approach Methodologies (NAMs) – innovative, non-animal technologies being designed to replace, reduce, or refine traditional animal testing – for chemical risk assessment will strengthen scientific confidence in existing quantitative risk assessment processes, including the TTC approach.

Interest by the CAC in developing guidance on food safety aspects related to the use of recycled plastics in food packaging will draw more global attention to this issue and foster regulatory harmonization across countries. Harmonizing global regulatory frameworks for recycled FCMs and non-synthetic alternatives (i.e. bio-based materials) will not only assist in developing a sound scientific risk assessment process but also aid in meeting existing and future global plastic waste reduction targets.



A worker transports large bags of produce on a cart at the market.

REFERENCES

- Alam, Md.J. & Rahman, Md.M. 2025. Challenges associated with preventive measures and environmentally acceptable techniques to control microplastics. In: *Microplastics*. pp. 441–449. Elsevier. <https://doi.org/10.1016/B978-0-443-29804-2.00019-6>
- Alamri, M.S., Qasem, A.A.A., Mohamed, A.A., Hussain, S., Ibraheem, M.A., Shamlan, G., Alqah, H.A. & Qasha, A.S. 2021. Food packaging's materials: A food safety perspective. *Saudi Journal of Biological Sciences*, 28(8): 4490–4499. <https://doi.org/10.1016/j.sjbs.2021.04.047>
- Ali-Hassanzadeh, M., Arefinia, N., Ghoreishi, Z.-A.-S., Askarpour, H. & Mashayekhi-Sardoo, H. 2025. The effects of exposure to microplastics on female reproductive health and pregnancy outcomes: A systematic review and meta-analysis. *Reproductive Toxicology*, 135: 108932. <https://doi.org/10.1016/j.reprotox.2025.108932>
- Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z. & Younis, K. 2022. Application of nanotechnology in food packaging: Pros and Cons. *Journal of Agriculture and Food Research*, 7: 100270. <https://doi.org/10.1016/j.jafr.2022.100270>
- Aversano, F. 2025. Food Packaging: Legislation and Regulatory Issues. In: *Antimicrobial Food Packaging*. pp. 293–300. Elsevier. <https://doi.org/10.1016/B978-0-323-90747-7.00018-1>
- Berk, Z. 2018. Food packaging. In: *Food Process Engineering and Technology*. pp. 625–641. Elsevier. <https://doi.org/10.1016/B978-0-12-812018-7.00027-0>
- Bharti, S., Pal, P. & Kumar, A. 2025. Toxicological Aspects of Nanomaterials in Food Packaging. In: A. Kumar, ed. *Nanotechnology in Food Packaging*. pp. 197–214. Cham, Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-82399-2_9
- Bonwick, G., Bradley, E., Lock, I. & Romero, R. 2019. Bio-Based Materials For Use In Food Contact Applications. Fera project number FR/001658. Report to the Food Standards Agency. June.
- Bouma, K., Kalsbeek-van Wijk, D., Steendam, L., Sijm, D.T.H.M., De Rijk, T., Kause, R., Hoogenboom, R. & Van Leeuwen, S. 2024. Plant-based food contact materials: presence of hazardous substances. *Food Additives & Contaminants: Part A*, 41(7): 846–855. <https://doi.org/10.1080/19440049.2024.2357350>
- Brazil. 2008. Resolução de Diretoria Colegiada (RDC) No20, de 26 de Marco de 2008; BRASIL: Brasília, Brazil, 2008.
- Brazil. 2016. Informe Técnico n. 71, de 11 de Fevereiro de 2016. BRASIL; Brasília, Brazil, 2016.
- Bronczyk, K., Dabrowska, A., Bielicka-Daszkiwicz, K. & Milczewska, K. 2025. Safety of new food contact materials: Migration and sorption studies based on Tenax, powdered milk, baby cereal and oat flakes. *Food Chemistry*, 483: 144148. <https://doi.org/10.1016/j.foodchem.2025.144148>

- CAA (Consumer Affairs Agency, Government of Japan). 2025. Positive List System for Food Utensils, Containers, and Packaging (From June 1, 2025) | Consumer Affairs Agency. [Cited 25 November 2025] https://www.caa.go.jp/policies/policy/standards_evaluation/applianCAAce/positive_list_new
- Cano, A., Cháfer, M., Chiralt, A. & González-Martínez, C. 2016. Development and characterization of active films based on starch-PVA, containing silver nanoparticles. *Food Packaging and Shelf Life*, 10: 16–24. <https://doi.org/10.1016/j.fpsl.2016.07.002>
- Cao, G., Lin, H., Kannan, P., Wang, C., Zhong, Y., Huang, Y. & Guo, Z. 2018. Enhanced Antibacterial and Food Simulant Activities of Silver Nanoparticles/Polypropylene Nanocomposite Films. *Langmuir*, 34(48): 14537–14545. <https://doi.org/10.1021/acs.langmuir.8b03061>
- Carmona, E., Rojo-Nieto, E., Rummel, C.D., Krauss, M., Syberg, K., Ramos, T.M., Brosche, S., Backhaus, T. & Almroth, B.C. 2023. A dataset of organic pollutants identified and quantified in recycled polyethylene pellets. *Data in Brief*, 51: 109740. <https://doi.org/10.1016/j.dib.2023.109740>
- Carney Almroth, B., Carmona, E., Chukwuone, N., Dey, T., Slunge, D., Backhaus, T. & Karlsson, T. 2025. Addressing the toxic chemicals problem in plastics recycling. *Cambridge Prisms: Plastics*, 3: e3. <https://doi.org/10.1017/plc.2025.1>
- Carullo, D. & Farris, S. 2025. Food packaging and potential microplastics release. In: *Microplastics in Agriculture and Food Science*. pp. 251–260. Elsevier. <https://doi.org/10.1016/B978-0-443-22210-8.00019-5>
- CCME (Canadian Council of Ministers of the Environment). 2019. Canada-wide action plan on zero plastic waste. [Cited 18 October, 2025] https://ccme.ca/en/res/1589_ccmecanada-wideactionplanonzeroplasticwaste_en-secured.pdf
- Chaïb, I., Doyen, P., Merveillie, P., Dehaut, A. & Duflos, G. 2025. Microplastic contaminations in a set of beverages sold in France. *Journal of Food Composition and Analysis*, 144: 107719. <https://doi.org/10.1016/j.jfca.2025.107719>
- Cramer, G.M., Ford, R.A. & Hall, R.L. 1978. Estimation of toxic hazard—a decision tree approach. *Food and Cosmetics Toxicology*, 16: 255–276. [https://doi.org/10.1016/S0015-6264\(76\)80522-6](https://doi.org/10.1016/S0015-6264(76)80522-6). Corrigendum.
- de la Cruz García, C., Moragas, G. S., & Nordqvist, D. 2023. Food contact materials. In V. Andersen, H. Lelieveld, & Y. Motarjemi (Eds.), *Food safety management*, pp. 385–402. Academic Press. <https://doi.org/10.1016/B978-0-12-820013-1.00047-4>
- Daggubati, L., Sobhani, Z., Carbery, M., Ramadass, K. & Palanisami, T. 2025. Fingerprinting risk from recycled plastic products using physical and chemical properties. *Journal of Hazardous Materials*, 488: 137507. <https://doi.org/10.1016/j.jhazmat.2025.137507>
- Dessi, C., Okoffo, E.D., O'Brien, J.W., Gallen, M., Samanipour, S., Kaserzon, S., Rauert, C., Wang, X. & Thomas, K.V. 2021. Plastics contamination of store-bought rice. *Journal of Hazardous Materials*, 416: 125778. <https://doi.org/10.1016/j.jhazmat.2021.125778>

- Duda, A. & Petka, K. 2025. The Presence of Micro- and Nanoplastics in Food and the Estimation of the Amount Consumed Depending on Dietary Patterns. *Molecules*, 30(18): 3666. <https://doi.org/10.3390/molecules30183666>
- Duncan, T.V., Khan, S.A., Patri, A.K. & Wiggins, S. 2024. Regulatory Science Perspective on the Analysis of Microplastics and Nanoplastics in Human Food. *Analytical Chemistry*, 96(11): 4343–4358. <https://doi.org/10.1021/acs.analchem.3c05408>
- EC (European Commission). 2009. Commission Regulation (EC) No. 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food. *Official Journal of the European Union*, 135: 3–11. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009R0450>
- EC. 2011. Commission Regulation (EC) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food. *Official Journal of the European Union*, 12: 1–89. <https://eur-lex.europa.eu/eli/reg/2011/10/oj/eng>
- EC. 2018. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions A European Strategy for Plastics in a Circular Economy. [Cited 24 November 2025]. https://environment.ec.europa.eu/strategy/plastics-strategy_en
- EC. 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A New Circular Economy Action Plan for a Cleaner and More Competitive Europe. https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF
- EC. 2022. Commission Regulation (EU) 2022/1616 of 15 September 2022 on recycled plastic materials and articles intended to come into contact with foods, and repealing regulation (EC) No 282/2008 (Text with EEA relevance). *Official Journal of the European Union*, 243: 3–46. <https://eur-lex.europa.eu/eli/reg/2022/1616/oj/eng>
- EC. 2025a. Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC (Text with EEA relevance). <https://eur-lex.europa.eu/eli/reg/2025/40/oj/eng>
- EC. 2025b. Commission Regulation (EU) 2025/351 of 21 February 2025 amending Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food, amending Regulation (EU) 2022/1616 on recycled plastic materials and articles intended to come into contact with foods, and repealing Regulation (EC) No 282/2008, and amending Regulation (EC) No 2023/2006 on good manufacturing practice for materials and articles intended to come into contact with food as regards recycled plastic and other matters related to quality control and manufacturing of plastic materials and articles intended to come into contact with food. <https://eur-lex.europa.eu/eli/reg/2025/351/oj/eng>
- ECCC (Environment and Climate Change Canada) & Health Canada. 2025. Science approach document on the prioritization of chemicals in plastics. [Cited 20 December 2025] [science-approach-document-prioritization-chemicals-plastics.pdf](#)

- EFSA (European Food Safety Authority), Barthélémy, E., Cariou, R., Castle, L., Crebelli, R., Di Consiglio, E., Dumas, T.H. *et al.* 2025. Literature review on micro- and nanoplastic release from food contact materials during their use. *EFSA Supporting Publications*, 22(10): EN-9733. <https://doi.org/10.2903/sp.efsa.2025.EN-9733>
- EFSA CEF Panel (EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids). 2016. Safety assessment of the substance zinc oxide, nanoparticles, for use in food contact materials. *EFSA Journal*, 14(3): 4408. <https://doi.org/10.2903/j.efsa.2016.4408>
- EFSA CEP Panel (EFSA Panel on Food Contact Materials, Enzymes and Processing Aids), Lambré, C., Barat Baviera, J. M., Bolognesi, C., Chesson, A., Cocconcelli, P. S., Crebelli, R. *et al.* 2024. Scientific Guidance on the criteria for the evaluation and on the preparation of applications for the safety assessment of post-consumer mechanical PET recycling processes intended to be used for manufacture of materials and articles in contact with food. *EFSA Journal*, 22(7): e8879. <https://doi.org/10.2903/j.efsa.2024.8879>
- EFSA Scientific Committee, More, S.J., Bampidis, V., Benford, D., Bragard, C., Halldorsson, T.I., Hernández-Jerez, A.F. *et al.* 2019. Guidance on the use of the Threshold of Toxicological Concern approach in food safety assessment. *EFSA Journal*, 17(6): 5708. <https://doi.org/10.2903/j.efsa.2019.5708>
- EFSA & WHO (European Food Safety Authority & World Health Organization). 2016. Review of the Threshold of Toxicological Concern (TTC) approach and development of new TTC decision tree. *EFSA Supporting Publications*, 13(3): EN-1006. <https://doi.org/10.2903/sp.efsa.2016.EN-1006>
- EHN (Environmental Health News). 2024. Is recycled plastic safe for food contact? If the company says so, according to the FDA. [Cited 30 August 2025]. <https://www.ehn.org/plastic-packaging-recycling>
- Ellen MacArthur Foundation & UNEP. 2023. The Global Commitment 2023. Progress Report. <https://content.ellenmacarthurfoundation.org/m/1b565394a67da8a5/original/The-Global-Commitment-2023-Progress-Report.pdf>
- Ezhava, S.R., Lobo, V.H. & Rodge, S.P. 2025. Hazards of microplastics on human health and its mitigation strategies. *Toxicology and Environmental Health Science*, 17: 177–190. <https://doi.org/10.1007/s13530-025-00249-9>
- FAO (Food and Agriculture Organization of the United Nations). 2019. The state of food and agriculture: moving forward on food loss and waste reduction. <https://www.fao.org/interactive/state-of-food-agriculture/2019/en/>
- FAO. 2022. *Thinking about the future of food safety - A foresight report*. Rome. <https://doi.org/10.4060/cb8667en>
- FAO. 2024. *Food safety in a circular economy*. Food Safety and Quality Series, No. 29. Rome. <https://doi.org/10.4060/cd1789en>
- FAO & WHO. 1993. *Code of Hygienic Practice for Aseptically Processed and Packaged Low-Acid Foods*. CXC 40-1993. Codex Alimentarius Commission. Rome. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXC%2B40-1993%252FCXC_040e.pdf

- FAO & WHO. 1995. *General Standard for Contaminants and Toxins in Food and Feed*. CXS 193-1995. Codex Alimentarius Commission. Rome. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252Fstandards%252FCXS%2B193-1995%252FCXS_193e.pdf
- FAO & WHO. 2019. *Guidelines for Rapid Risk Analysis Following Instances of Detection of Contaminants in Food where There Is No Regulatory Level*. CXG 92-2019. Codex Alimentarius Commission. Rome. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/ar/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXG%2B92-2019%252FCXG_092e.pdf
- FAO & WHO. 2023a. *General Principles of Food Hygiene*. Codex Alimentarius Code of Practice, No. CXC 1-1969. Codex Alimentarius Commission. Rome. <https://doi.org/10.4060/cc6125en>
- FAO & WHO. 2023b. *Codex Alimentarius Commission Forty-sixth Session, FAO Headquarters, Rome, Italy, 27 November–2 December 2023: Report of the Eighty-fifth Session of the Executive Committee of the Codex Alimentarius Commission*. REP23/EXEC2. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/pl/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FMeetings%252FCX-702-85%252FFINAL%252520REP23_EXEC2%252FREP23_EXEC2e.pdf
- FAO & WHO. 2023c. *Joint FAO/WHO Food Standards Programme Codex Alimentarius Commission Forty-sixth Session*. REP23/CAC. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FMeetings%252FCX-701-46%252F%25E2%2598%2585Final%252520Report%252FREP23_CACe.pdf
- FAO & WHO. 2024. *Joint FAO/WHO Food Standards Programme, Codex Alimentarius Commission Forty-seventh Session: Report of the Eighty-sixth Session of the Executive Committee of the Codex Alimentarius Commission*. REP24/EXEC1. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/fr/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FMeetings%252FCX-702-86%252FFinal%252520REPORT%252FREP24_EXEC1e.pdf
- FAO & WHO. 2025. *Joint FAO/WHO Food Standards Programme, Codex Alimentarius Commission Forty-eighth Session: Report of the 18th Session of the Codex Committee on Contaminants in Foods*. REP25/CF18. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FMeetings%252FCX-735-18%252FREPORT%252FFINAL%2BREPORT%252FREP25_CF18e.pdf
- Federal Register. 1995. Vol. 60, No. 136. Food Additives; Threshold of Regulation for Substances Used in Food-Contact Articles.
- Frawley, J.P. 1967. Scientific evidence and common sense as a basis for food-packaging regulations. *Food and Cosmetics Toxicology*, 5(3): 293–308. [https://doi.org/10.1016/S0015-6264\(67\)83055-4](https://doi.org/10.1016/S0015-6264(67)83055-4)

- Gabisa, E.W., Ratanatamskul, C. & Gheewala, S.H. 2023. Recycling of Plastics as a Strategy to Reduce Life Cycle GHG Emission, Microplastics and Resource Depletion. *Sustainability*, 15(15): 11529. <https://doi.org/10.3390/su151511529>
- Gao, B., Chen, L., Wu, L., Zhang, S., Zhao, S., Mo, Z., Chen, Z. & Tu, P. 2025. Association between microplastics and the functionalities of human gut microbiome. *Ecotoxicology and Environmental Safety*, 290: 117497. <https://doi.org/10.1016/j.ecoenv.2024.117497>
- Garrido Gamarro, E. & Costanzo, V. 2022a. *Microplastics in food commodities – A food safety review on human exposure through dietary sources*. Food Safety and Quality Series No. 18. Rome, FAO. <https://doi.org/10.4060/cc2392en>
- Garrido Gamarro, E. & Costanzo, V. 2022b. Dietary Exposure to Additives and Sorbed Contaminants from Ingested Microplastic Particles Through the Consumption of Fisheries and Aquaculture Products. In: M.S. Bank, ed. *Microplastic in the Environment: Pattern and Process*. pp. 261–310. Environmental Contamination Remediation and Management. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-030-78627-4_8
- Geueke, B., Groh, K. & Muncke, J. 2018. Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. *Journal of Cleaner Production*, 193: 491–505. <https://doi.org/10.1016/j.jclepro.2018.05.005>
- Geueke, B., Phelps, D.W., Parkinson, L.V. & Muncke, J. 2023. Hazardous chemicals in recycled and reusable plastic food packaging. *Cambridge Prisms: Plastics*, 1: e7. <https://doi.org/10.1017/plc.2023.7>
- Geueke, B., Parkinson, L.V., Groh, K.J., Kassotis, C.D., Maffini, M.V., Martin, O.V., Zimmermann, L., Scheringer, M. & Muncke, J. 2025. Evidence for widespread human exposure to food contact chemicals. *Journal of Exposure Science & Environmental Epidemiology*, 35(3): 330–341. <https://doi.org/10.1038/s41370-024-00718-2>
- Geyer, R., Jambeck, J.R. & Law, K.L. 2017. Production, use, and fate of all plastics ever made. *Science Advances*, 3(7): e1700782. <https://doi.org/10.1126/sciadv.1700782>
- Global Plastic Action Partnership. 2022. Global Plastics Treaty – Toward a legally binding international agreement to end plastic pollution. [Cited 23 October 2025]. <https://www.globalplasticaction.org/globalplasticstreaty>
- Government of Japan. 2019. Japan's Resource Circulation Strategy for Plastics (May 2019). [Cited 24 October 2025]. <https://www.env.go.jp/content/000050297.pdf>
- Groh, K.J., Geueke, B., Martin, O., Maffini, M. & Muncke, J. 2021. Overview of intentionally used food contact chemicals and their hazards. *Environment International*, 150: 106225. <https://doi.org/10.1016/j.envint.2020.106225>
- Gune, R. & Martin, A. 2025. Microplastics in our diet: A review of food source contamination. *Food Control*, 178: 111486. <https://doi.org/10.1016/j.foodcont.2025.111486>
- Gupta, R.K., Guha, P. & Srivastav, P.P. 2024. Investigating the toxicological effects of nanomaterials in food packaging associated with human health and the environment. *Journal of Hazardous Materials Letters*, 5: 100125. <https://doi.org/10.1016/j.hazl.2024.100125>

- Gupta, R.K., Pipliya, S., Karunanithi, S., Eswaran U, G.M., Kumar, S., Mandliya, S., Srivastav, P.P. *et al.* 2024. Migration of Chemical Compounds from Packaging Materials into Packaged Foods: Interaction, Mechanism, Assessment, and Regulations. *Foods*, 13(19): 3125. <https://doi.org/10.3390/foods13193125>
- Harnkarnsujarit, N., Wongphan, P., Chatkitanan, T., Laurenza, Y. & Srisa, A. 2021. Bioplastic for Sustainable Food Packaging. In: *Sustainable Food Processing and Engineering Challenges*. pp. 203–277. Elsevier. <https://doi.org/10.1016/B978-0-12-822714-5.00007-3>
- He, Y.-J., Qin, Y., Zhang, T.-L., Zhu, Y.-Y., Wang, Z.-J., Zhou, Z.-S., Xie, T.-Z. & Luo, X.-D. 2021. Migration of (non-) intentionally added substances and microplastics from microwavable plastic food containers. *Journal of Hazardous Materials*, 417: 126074. <https://doi.org/10.1016/j.jhazmat.2021.126074>
- Health Canada. 2022. Policy Statement on Health Canada’s Working Definition for Nanomaterial. [Cited 29 October 2025]. <https://www.canada.ca/en/health-canada/services/science-research/reports-publications/nanomaterial/policy-statement-health-canada-working-definition.html>
- Health Canada. 2023. Packaging Materials. Food Packaging Regulations. [Cited 24 October 2024]. <https://www.canada.ca/en/health-canada/services/food-nutrition/food-safety/packaging-materials.html>
- Health Canada & ECCC (Environment and Climate Change Canada). 2020. Science assessment of plastic pollution. [Cited 30 November 2025] <https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/science-assessment-plastic-pollution.html>
- Hoang, H.G., Nguyen, N.S.H., Zhang, T., Tran, H.-T., Mukherjee, S. & Naidu, R. 2025. A review of microplastic pollution and human health risk assessment: current knowledge and future outlook. *Frontiers in Environmental Science*, 13: 1606332. <https://doi.org/10.3389/fenvs.2025.1606332>
- Houssini, K., Li, J. & Tan, Q. 2025. Complexities of the global plastics supply chain revealed in a trade-linked material flow analysis. *Communications Earth & Environment*, 6(1): 257. <https://doi.org/10.1038/s43247-025-02169-5>
- Hu, Y. & Li, T. 2024. Smart food packaging: Recent advancement and trends. In: *Advances in Food and Nutrition Research*. pp. 1–33. Vol. 111. Elsevier. <https://doi.org/10.1016/bs.afnr.2024.06.005>
- Huang, S., Dong, Q., Che, S., Li, R. & Tang, K.H.D. 2025. Bioplastics and biodegradable plastics: A review of recent advances, feasibility and cleaner production. *Science of The Total Environment*, 969: 178911. <https://doi.org/10.1016/j.scitotenv.2025.178911>
- Hussain, S., Akhter, R. & Maktedar, S.S. 2024. Advancements in sustainable food packaging: from eco-friendly materials to innovative technologies. *Sustainable Food Technology*, 2(5): 1297–1364. <https://doi.org/10.1039/D4FB00084F>
- Jadhav, E.B., Sankhla, M.S., Bhat, R.A. & Bhagat, D.S. 2021. Microplastics from food packaging: An overview of human consumption, health threats, and alternative solutions. *Environmental Nanotechnology, Monitoring & Management*, 16: 100608. <https://doi.org/10.1016/j.enmm.2021.100608>

- Jahangiri, F., Mohanty, A.K. & Misra, M. 2024. Sustainable biodegradable coatings for food packaging: challenges and opportunities. *Green Chemistry*, 26(9): 4934–4974. <https://doi.org/10.1039/D3GC02647G>
- Jangid, H., Joshi, H.C., Dutta, J., Ahmad, A., Alshammari, M.B., Hossain, K., Pant, G. & Kumar, G. 2025. Advancing food safety with biogenic silver nanoparticles: Addressing antimicrobial resistance, sustainability, and commercial viability. *Food Chemistry: X*, 26: 102298. <https://doi.org/10.1016/j.fochx.2025.102298>
- Janzik, R., Sieg, H., Braeuning, A. & Böhl, G.-F. 2025. Microplastics: State of the evidence on health effects and public perception. *Deutsches Ärzteblatt international*, 122: 546–51. <https://doi.org/10.3238/arztebl.m2025.0138>
- Järvelä, E., Peräniemi, S., Vepsäläinen, J., Hrovat, B., Raninen, K., Tomppo, L., Koistinen, A. & Rysä, J. 2025. A study protocol for chemical analysis and toxicity testing of virgin and recycled microplastics and associated chemicals. *Science of The Total Environment*, 975: 179287. <https://doi.org/10.1016/j.scitotenv.2025.179287>
- Jehanno, C., Ximenis, M., Breloy, L., Akin, O., Kol, R., Van Geem, K.M., De Meester, S. & Sardón, H. 2025. What decades of plastics waste management have taught us. *Nature Reviews Materials*, 10(10): 715–716. <https://doi.org/10.1038/s41578-025-00820-3>
- Jenner, L.C., Rotchell, J.M., Bennett, R.T., Cowen, M., Tentzeris, V. & Sadofsky, L.R. 2022. Detection of microplastics in human lung tissue using μ FTIR spectroscopy. *Science of The Total Environment*, 831: 154907. <https://doi.org/10.1016/j.scitotenv.2022.154907>
- Kato, L.S. & Conte-Junior, C.A. 2021. Safety of Plastic Food Packaging: The Challenges about Non-Intentionally Added Substances (NIAS) Discovery, Identification and Risk Assessment. *Polymers*, 13(13): 2077. <https://doi.org/10.3390/polym13132077>
- Khatoon, N., Ali, S., Huang, J., Yu, Z. & Liu, H. 2025. Microplastics in Essential Food Commodities: A Systematic Review of identification, detection, contamination, and Health Implications (2017–2024). *Food Reviews International*: 1–35. <https://doi.org/10.1080/87559129.2025.2514252>
- Khu, S.-T., Li, F. & Zhao, W. 2025. Microplastics in drinking water distribution systems: Occurrence, environmental behavior, and human health concerns. *Environmental Pollution*, 382: 126666. <https://doi.org/10.1016/j.envpol.2025.126666>
- Koshy, J.T., Vasudevan, D., Sangeetha, D. & Prabu, A.A. 2023. Biopolymer based multifunctional films loaded with anthocyanin rich floral extract and ZnO nano particles for smart packaging and wound healing applications. *Polymers*, 15(10): 2372. <https://doi.org/10.3390/polym15102372>
- Kroes, R., Renwick, A.G., Cheeseman, M., Kleiner, J., Mangelsdorf, I., Piersma, A., Schilter, B. *et al.* 2004. Structure-based thresholds of toxicological concern (TTC): guidance for application to substances present at low levels in the diet. *Food and Chemical Toxicology*, 42(1): 65–83. <https://doi.org/10.1016/j.fct.2003.08.006>
- Kumar, R., Kutagulla, T., Vasudevan, V., George, J. & Semwal, A.D. 2025. New Perspectives in Intelligent Food Packaging. *Journal of Packaging Technology and Research*, 9(1): 59–76. <https://doi.org/10.1007/s41783-025-00182-9>

- Kumar, S. & Prasad, E.** 2021. Packaged Food Market Size, Share, Competitive Landscape and Trend Analysis Report, by Type (Dairy Products, Confectionery, Packaged Produce, Bakery & Snacks, Meat, Poultry & Seafood, Ready Meals, and Others), Sales Channel (Supermarket/Hypermarket, Specialty Stores, Grocery Stores, Online Stores, and Others: Global Opportunity Analysis and Industry Forecast, 2021-2030. In: Applied Market Research. [Cited 17 December 2025]. <https://www.alliedmarketresearch.com/packaged-food-market>
- Lacourt, C., Mukherjee, K., Garthoff, J., O’Sullivan, A., Meunier, L. & Fattori, V.** 2024. Recent and emerging food packaging alternatives: Chemical safety risks, current regulations, and analytical challenges. *Comprehensive Reviews in Food Science and Food Safety*, 23(6): e70059. <https://doi.org/10.1111/1541-4337.70059>
- Lamoree, M.H., Van Boxel, J., Nardella, F., Houthuijs, K.J., Brandsma, S.H., Béen, F. & Van Duursen, M.B.M.** 2025. Health impacts of microplastic and nanoplastic exposure. *Nature Medicine*, 31(9): 2873–2887. <https://doi.org/10.1038/s41591-025-03902-5>
- Leal Filho, W., Barbir, J., Venkatesan, M., Lange Salvia, A., Dobri, A., Bošković, N., Eustachio, J.H.P.P., Ingram, I. & Dinis, M.A.P.** 2025. Policy Gaps and Opportunities in Bio-Based Plastics: Implications for Sustainable Food Packaging. *Foods*, 14(11): 1955. <https://doi.org/10.3390/foods14111955>
- Leslie, H.A., Van Velzen, M.J.M., Brandsma, S.H., Vethaak, A.D., Garcia-Vallejo, J.J. & Lamoree, M.H.** 2022. Discovery and quantification of plastic particle pollution in human blood. *Environment International*, 163: 107199. <https://doi.org/10.1016/j.envint.2022.107199>
- Lestido-Cardama, A., Barbosa-Pereira, L., Sendón, R., Bustos, J., Paseiro Losada, P. & Rodríguez Bernaldo De Quirós, A.** 2025. Chemical safety and risk assessment of bio-based and/or biodegradable polymers for food contact: A review. *Food Research International*, 202: 115737. <https://doi.org/10.1016/j.foodres.2025.115737>
- Li, Y., Tao, L., Wang, Q., Wang, F., Li, G. & Song, M.** 2023. Potential Health Impact of Microplastics: A Review of Environmental Distribution, Human Exposure, and Toxic Effects. *Environment & Health*, 1(4): 249–257. <https://doi.org/10.1021/envhealth.3c00052>
- Li, Y., Ling, W., Yang, J. & Xing, Y.** 2025. Risk Assessment of Microplastics in Humans: Distribution, Exposure, and Toxicological Effects. *Polymers*, 17(12): 1699. <https://doi.org/10.3390/polym17121699>
- Lin, S., Chen, L., Huang, L., Cao, S., Luo, X. & Liu, K.** 2015. Novel antimicrobial chitosan–cellulose composite films bioconjugated with silver nanoparticles. *Industrial Crops and Products*, 70: 395–403. <https://doi.org/10.1016/j.indcrop.2015.03.040>
- Liu, Q., Fang, J., Liu, Z., Chen, Y., Chen, Q., Chen, Z., Yuan, S., Yu, H. & Yao, W.** 2025. Influence of different food matrices on the abundance, characterization, migration kinetics and hazards of microplastics released from plastic packaging (PP and PET). *Food Chemistry*, 478: 143691. <https://doi.org/10.1016/j.foodchem.2025.143691>
- López Sanvicente, E., Barbosa-Pereira, L., Sendón, R., Rodríguez Bernaldo De Quirós, A. & Lestido-Cardama, A.** 2025. Identification of Potential Migrants in Food Contact Materials Labeled as Bio-Based and/or Biodegradable by GC-MS. *Coatings*, 15(7): 751. <https://doi.org/10.3390/coatings15070751>

- Luo, Q., Tan, H., Ye, M., Jho, E.H., Wang, P., Iqbal, B., Zhao, X. *et al.* 2025. Microplastics as an emerging threat to human health: An overview of potential health impacts. *Journal of Environmental Management*, 387: 125915. <https://doi.org/10.1016/j.jenvman.2025.125915>
- Mahmud, J., Sarmast, E., Shankar, S. & Lacroix, M. 2022. Advantages of nanotechnology developments in active food packaging. *Food Research International*, 154: 111023. <https://doi.org/10.1016/j.foodres.2022.111023>
- Marcelino, C.S., Gomes, V.E.D.S. & Marangoni Júnior, L. 2025. Post-Consumer Recycled PET: A Comprehensive Review of Food and Beverage Packaging Safety in Brazil. *Polymers*, 17(5): 594. <https://doi.org/10.3390/polym17050594>
- McIlwraith, H.K., Lindeque, P.K., Tolhurst, T.J. & Cole, M. 2025. Positive controls with representative materials are essential for the advancement of microplastics research. *Microplastics and Nanoplastics*, 5(1): 9. <https://doi.org/10.1186/s43591-025-00115-y>
- Merrington, A. 2024. Recycling of Plastics. In: *Applied Plastics Engineering Handbook*. pp. 191–217. Elsevier. <https://doi.org/10.1016/B978-0-323-88667-3.00006-0>
- Mihalca, V., Kerezsi, A.D., Weber, A., Gruber-Traub, C., Schmucker, J., Vodnar, D.C., Dulf, F.V. *et al.* 2021. Protein-Based Films and Coatings for Food Industry Applications. *Polymers*, 13(5): 769. <https://doi.org/10.3390/polym13050769>
- Miralles, P., Fuentes-Ferragud, E., Socas-Hernández, C. & Coscollà, C. 2025. Recent Trends and Challenges on the Non-Targeted Analysis and Risk Assessment of Migrant Non-Intentionally Added Substances from Plastic Food Contact Materials. *Toxics*, 13(7): 543. <https://doi.org/10.3390/toxics13070543>
- Mkhari, T., Adeyemi, J.O. & Fawole, O.A. 2025. Recent Advances in the Fabrication of Intelligent Packaging for Food Preservation: A Review. *Processes*, 13(2): 539. <https://doi.org/10.3390/pr13020539>
- Monclús, L., Arp, H.P.H., Groh, K.J., Faltynkova, A., Løseth, M.E., Muncke, J., Wang, Z. *et al.* 2025. Mapping the chemical complexity of plastics. *Nature*, 643(8071): 349–355. <https://doi.org/10.1038/s41586-025-09184-8>
- Mossburger, J. & Scherf, K.A. 2024. Gluten migration from biodegradable food contact materials poses a risk to celiac disease patients. *European Food Research and Technology*, 250(11): 2711–2718. <https://doi.org/10.1007/s00217-024-04570-4>
- Muncke, J., Backhaus, T., Brander, S., Fini, J.-B., Gündoğdu, S., Schür, C., Zimmermann, L. & Scheringer, M. 2025. Comment on “Microplastic contaminations in a set of beverages sold in France” by Chaïb *et al.* *Journal of Food Composition and Analysis*, 148: 108310. <https://doi.org/10.1016/j.jfca.2025.108310>
- Munro, I.C. 1990. Safety assessment procedures for indirect food additives: an overview. Report of a workshop. *Regulatory Toxicology and Pharmacology*, 12(1): 2–12. [https://doi.org/10.1016/s0273-2300\(05\)80042-x](https://doi.org/10.1016/s0273-2300(05)80042-x)
- Munro, I.C., Ford, R.A., Kennepohl, E. & Sprenger, J.G. 1996. Correlation of structural class with no-observed effect levels: a proposal for establishing a threshold of concern. *Food and Chemical Toxicology*, 34(9): 829–867. [https://doi.org/10.1016/s0278-6915\(96\)00049-x](https://doi.org/10.1016/s0278-6915(96)00049-x)

- Munro, I.C., Renwick, A.G. & Danielewska-Nikiel, B. 2008. The Threshold of Toxicological Concern (TTC) in risk assessment. *Toxicology Letters*, 180(2): 151–156. <https://doi.org/10.1016/j.toxlet.2008.05.006>
- Muzeza, C., Ngole-Jeme, V. & Msagati, T.A.M. 2023. The Mechanisms of Plastic Food-Packaging Monomers' Migration into Food Matrix and the Implications on Human Health. *Foods*, 12(18): 3364. <https://doi.org/10.3390/foods12183364>
- Naseer, B., Srivastava, G., Qadri, O.S., Faridi, S.A., Islam, R.U. & Younis, K. 2018. Importance and health hazards of nanoparticles used in the food industry. *Nanotechnology Reviews*, 7(6): 623–641. <https://doi.org/10.1515/ntrev-2018-0076>
- Ncube, L.K., Ude, A.U., Ogunmuyiwa, E.N., Zulkifli, R. & Beas, I.N. 2020. Environmental Impact of Food Packaging Materials: A Review of Contemporary Development from Conventional Plastics to Polylactic Acid Based Materials. *Materials*, 13(21): 4994. <https://doi.org/10.3390/ma13214994>
- Nerín, C., Bourdoux, S., Faust, B., Gude, T., Lesueur, C., Simat, T., Stoermer, A., Van Hoek, E. & Oldring, P. 2022. Guidance in selecting analytical techniques for identification and quantification of non-intentionally added substances (NIAS) in food contact materials (FCMS). *Food Additives & Contaminants: Part A*, 39(3): 620–643. <https://doi.org/10.1080/19440049.2021.2012599>
- Nerin, C., Boobis, A.R., Debarata, K., Dubail, S., Gude, T., Kirchnawy, C., Knaup, B. *et al.* 2025. Review of potential areas for global harmonization of risk assessment protocols for Food Contact Materials (FCMs). *Trends in Food Science & Technology*, 159: 104987. <https://doi.org/10.1016/j.tifs.2025.104987>
- Nouri, M., Massahi, T. & Hossini, H. 2025. Microplastics in human body: a narrative on routes of exposure to contamination and potential health effects. *Environmental Pollutants and Bioavailability*, 37(1): 2538535. <https://doi.org/10.1080/26395940.2025.2538535>
- OECD (Organisation for Economic Co-operation and Development). 2022. *Global Plastics Outlook: Policy Scenarios to 2060*. OECD Publishing, Paris. <https://doi.org/10.1787/aa1edf33-en>
- Operato, L., Panzeri, A., Masoero, G., Gallo, A., Gomes, L. & Hamd, W. 2025. Food packaging use and post-consumer plastic waste management: a comprehensive review. *Frontiers in Food Science and Technology*, 5: 1520532. <https://doi.org/10.3389/frfst.2025.1520532>
- Panigrahy, M. & Rout, G.R. 2025. Nanomaterials in food processing, packaging preservation and their effects on health & environment. *European Food Research and Technology*, 251(5): 861–875. <https://doi.org/10.1007/s00217-025-04676-3>
- Panou, A. & Karabagias, I.K. 2024. Migration and Safety Aspects of Plastic Food Packaging Materials: Need for Reconsideration? *Coatings*, 14(2): 168. <https://doi.org/10.3390/coatings14020168>
- Pathak, G., Mangla, S. & Bhan, V. 2025. Microplastics in the food chain. In: *Microplastics*. pp. 31–57. Elsevier. <https://doi.org/10.1016/B978-0-443-29804-2.00002-0>

- Pawde, S.V., Kaewprachu, P., Kingwascharapong, P., Sai-Ut, S., Karbowski, T., Jung, Y.H. & Rawdkuen, S. 2025. A comprehensive review on plant protein-based food packaging: Beyond petroleum-based polymers. *Current Research in Food Science*, 10: 101104. <https://doi.org/10.1016/j.crfs.2025.101104>
- Pearson, A.J., Mukherjee, K., Fattori, V. & Lipp, M. 2024. Opportunities and challenges for global food safety in advancing circular policies and practices in agrifood systems. *npj Science of Food*, 8(1): 60. <https://doi.org/10.1038/s41538-024-00286-7>
- Peng, B., Qin, J., Li, Y., Wu, K., Kuang, Y. & Jiang, F. 2024. Recent advances in nanomaterials-enabled active food packaging: Nanomaterials synthesis, applications and future prospects. *Food Control*, 163: 110542. <https://doi.org/10.1016/j.foodcont.2024.110542>
- Ragusa, A., Svelato, A., Santacrose, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F. *et al.* 2021. Plasticenta: First evidence of microplastics in human placenta. *Environment International*, 146: 106274. <https://doi.org/10.1016/j.envint.2020.106274>
- Ren, J., Wang, S., Gao, C., Chen, X., Li, W. & Peng, F. 2015. TiO₂-containing PVA/xylan composite films with enhanced mechanical properties, high hydrophobicity and UV shielding performance. *Cellulose*, 22(1): 593–602. <https://doi.org/10.1007/s10570-014-0482-1>
- Rosenboom, J.-G., Langer, R. & Traverso, G. 2022. Bioplastics for a circular economy. *Nature Reviews Materials*, 7(2): 117–137. <https://doi.org/10.1038/s41578-021-00407-8>
- Roy, B., Saikia, D., Nayak, P.K., Biswas, S.C., Bandyopadhyay, T.K., Bhunia, B. & Nath, P.C. 2023. Chapter 3 - Innovations in smart packaging technologies for monitoring of food quality and safety. Eds: Inamuddin, T. Altalhi & J. Nevez Cruz. *Green Sustainable Process for Chemical and Environmental Engineering and Science, Methods for Producing Smart Packaging*. pp. 39–58. Elsevier. <https://doi.org/10.1016/B978-0-323-95644-4.00013-9>
- Ruggieri, F., Battistini, B., Sorbo, A., Senofonte, M., Leso, V., Iavicoli, I. & Bocca, B. 2025. From food-to-human microplastics and nanoplastics exposure and health effects: A review on food, animal and human monitoring data. *Food and Chemical Toxicology*, 196: 115209. <https://doi.org/10.1016/j.fct.2024.115209>
- Rung, C., Welle, F., Gruner, A., Springer, A., Steinmetz, Z. & Munoz, K. 2023. Identification and Evaluation of (Non-)Intentionally Added Substances in Post-Consumer Recyclates and Their Toxicological Classification. *Recycling*, 8(1): 24. <https://doi.org/10.3390/recycling8010024>
- Saha, N.C. 2022. Food Packaging: Concepts and Its Significance. In: *Food Packaging*. pp. 1–45. Lecture Notes in Management and Industrial Engineering. Singapore, Springer Nature Singapore. https://doi.org/10.1007/978-981-16-4233-3_1
- Sajedi, S., An, C. & Chen, Z. 2025. Unveiling the hidden chronic health risks of nano- and microplastics in single-use plastic water bottles: A review. *Journal of Hazardous Materials*, 495: 138948. <https://doi.org/10.1016/j.jhazmat.2025.138948>

- Salvia, R., Soriano, C., Casanovas, I., Sorigué, M., Evans, E., De Pablo, J.G., Ward, M.D. & Petriz, J. 2025. Nanoplastic Contamination Across Common Beverages and Infant Food: An Assessment of Packaging Influence. *Microplastics*, 4(4): 108. <https://doi.org/10.3390/microplastics4040108>
- Sepúlveda-Carter, J., Moreno De Castro, J.L., Marín, L., Baños, P., Rodríguez, M.S. & Arrieta, M.P. 2025. Regulatory Frameworks and State-of-the-Art Decontamination Technologies for Recycled Polystyrene for Food Contact Applications. *Polymers*, 17(5): 658. <https://doi.org/10.3390/polym17050658>
- Seref, N. & Cufaoglu, G. 2025. Food Packaging and Chemical Migration: A Food Safety Perspective. *Journal of Food Science*, 90(5): e70265. <https://doi.org/10.1111/1750-3841.70265>
- Severin, I., Dahbi, L., Domenek, S., Nguyen, P.-M., Platel, A., Vitrac, O. & Chagnon, M.C. 2023. Stratégie pour une sécurité chimique intégrée des matériaux d'emballage au contact des denrées alimentaires. *Cahiers de Nutrition et de Diététique*, 58(2): 134–141. <https://doi.org/10.1016/j.cnd.2022.12.005>
- Sharma, V.K., Ma, X., Lichtfouse, E. & Robert, D. 2023. Nanoplastics are potentially more dangerous than microplastics. *Environmental Chemistry Letters*, 21(4): 1933–1936. <https://doi.org/10.1007/s10311-022-01539-1>
- Shi, X., Cui, L., Xu, C. & Wu, S. 2025. Next-Generation Bioplastics for Food Packaging: Sustainable Materials and Applications. *Materials*, 18(12): 2919. <https://doi.org/10.3390/ma18122919>
- Singh, S.S., Gigi, A.A., Pillai, P.K.S. & Ragavan, K.V. 2025. Global Regulatory Frameworks for Nanomaterials in Food Packaging. In: C. Anandharamakrishnan, J.A. Moses & M.M. Leena, eds. *Nanotechnology for Sustainable Food Packaging*. First edition, pp. 381–407. Wiley. <https://doi.org/10.1002/9781119875154.ch16>
- Soltani Firouz, M., Mohi-Alden, K. & Omid, M. 2021. A critical review on intelligent and active packaging in the food industry: Research and development. *Food Research International*, 141: 110113. <https://doi.org/10.1016/j.foodres.2021.110113>
- Stapleton, M.J., Ansari, A.J., Ahmed, A. & Hai, F.I. 2023. Evaluating the generation of microplastics from an unlikely source: The unintentional consequence of the current plastic recycling process. *Science of The Total Environment*, 902: 166090. <https://doi.org/10.1016/j.scitotenv.2023.166090>
- Störmer, A., Bott, J., Kemmer, D. & Franz, R. 2017. Critical review of the migration potential of nanoparticles in food contact plastics. *Trends in Food Science & Technology*, 63: 39–50. <https://doi.org/10.1016/j.tifs.2017.01.011>
- Suzuki, G., Uchida, N., Tuyen, L.H., Tanaka, K., Matsukami, H., Kunisue, T., Takahashi, S. *et al.* 2022. Mechanical recycling of plastic waste as a point source of microplastic pollution. *Environmental Pollution*, 303: 119114. <https://doi.org/10.1016/j.envpol.2022.119114>
- Suzuki, G., Uchida, N., Tanaka, K., Higashi, O., Takahashi, Y., Kuramochi, H., Yamaguchi, N. & Osako, M. 2024. Global discharge of microplastics from mechanical recycling of plastic waste. *Environmental Pollution*, 348: 123855. <https://doi.org/10.1016/j.envpol.2024.123855>

- Tan, W., Cui, D. & Xi, B. 2021. Moving policy and regulation forward for single-use plastic alternatives. *Frontiers of Environmental Science & Engineering*, 15(3): 50. <https://doi.org/10.1007/s11783-021-1423-5>
- Tang, M., Chen, C., Song, J., Ni, Y., Xiang, B., Zou, J. & Xu, D. 2024. Safety of plant fiber-based food contact materials: Overview of the discovery, identification, detection and risk assessment of unknown risk substances. *Food Packaging and Shelf Life*, 43: 101281. <https://doi.org/10.1016/j.fpsl.2024.101281>
- Teixeira-Costa, B.E. & Andrade, C.T. 2022. Natural Polymers Used in Edible Food Packaging—History, Function and Application Trends as a Sustainable Alternative to Synthetic Plastic. *Polysaccharides*, 3(1): 32–58. <https://doi.org/10.3390/polysaccharides3010002>
- Tenhunen-Lunkka, A., Rommens, T., Vanderreydt, I. & Mortensen, L. 2023. Greenhouse gas emission reduction potential of European Union’s circularity related targets for plastics. *Circular Economy and Sustainability*, 3(1): 475–510. <https://doi.org/10.1007/s43615-022-00192-8>
- Thin, Z.S., Chew, J., Ong, T.Y.Y., Raja Ali, R.A. & Gew, L.T. 2025. Impact of microplastics on the human gut microbiome: a systematic review of microbial composition, diversity, and metabolic disruptions. *BMC Gastroenterology*, 25(1): 583. <https://doi.org/10.1186/s12876-025-04140-2>
- Tumu, K., Vorst, K. & Curtzwiler, G. 2024. Understanding intentionally and non-intentionally added substances and associated threshold of toxicological concern in post-consumer polyolefin for use as food packaging materials. *Heliyon*, 10(1): e23620. <https://doi.org/10.1016/j.heliyon.2023.e23620>
- Uhlig, E., Sadzik, A., Strenger, M., Schneider, A.M. & Schmid, M. 2025. Food wastage along the global food supply chain and the impact of food packaging. *Journal of Consumer Protection and Food Safety*, 20: 5–17. <https://doi.org/10.1007/s00003-024-01539-z>
- UNEP (United Nations Environment Programme). 2021. Food Waste Index Report 2021. Nairobi. <https://www.unep.org/resources/report/unep-food-waste-index-report-2021>
- UNEP. 2024. Food Waste Index Report 2024. <https://www.unep.org/resources/publication/food-waste-index-report-2024>
- UNEP and Secretariat of the Basel, Rotterdam and Stockholm Conventions. 2023. Chemicals in plastics: a technical report. Geneva. <https://www.unep.org/resources/report/chemicals-plastics-technical-report>
- US FDA (United States Food and Drug Administration). 1995. Food additives: threshold of regulation for substances used in food contact articles; final rule. *21 CFR Part 5*.
- US FDA. 2018. Nanotechnology Guidance Documents. [Cited 24 October 2025]. <https://www.fda.gov/science-research/nanotechnology-programs-fda/nanotechnology-guidance-documents>

- US FDA. 2021. Guidance for Industry: Use of Recycled Plastics in Food Packaging (Chemistry Considerations). [23 October 2025]. <https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-use-recycled-plastics-food-packaging-chemistry-considerations>
- US FDA Human Foods Program. 2025. FDA Alerts Industry and Consumers about Palm Leaf Dinnerware. [Cited 1 December 2025]. <https://www.fda.gov/food/hfp-constituent-updates/fda-alerts-industry-and-consumers-about-palm-leaf-dinnerware>
- Vanderroost, M., Ragaert, P., Devlieghere, F. & De Meulenaer, B. 2014. Intelligent food packaging: The next generation. *Trends in Food Science & Technology*, 39(1): 47–62. <https://doi.org/10.1016/j.tifs.2014.06.009>
- Vats, T., Arora, G. & Tiwari, P. 2024. Application of metal oxide/metal nanoparticle-based antimicrobial films in food packaging: Potential use, risk factors, safety assessments and regulatory matters. *Journal of Applied Research and Technology*, 22(6): 926–942. <https://doi.org/10.22201/icat.24486736e.2024.22.6.2473>
- Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O.V. & García, M.A. 2023. Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations. *Foods*, 12(5): 1057. <https://doi.org/10.3390/foods12051057>
- Vinod, A., Sanjay, M.R., Suchart, S. & Jyotishkumar, P. 2020. Renewable and sustainable biobased materials: An assessment on biofibers, biofilms, biopolymers and biocomposites. *Journal of Cleaner Production*, 258: 120978. <https://doi.org/10.1016/j.jclepro.2020.120978>
- Wagner, M., Monclús, L., Arp, H.P.H., Groh, K.J., Løseth, M.E., Muncke, J., Wang, Z. & Wolf, R. 2024. State of the Science on Plastic Chemicals—Identifying and Addressing Chemicals and Polymers of Concern. Norwegian University of Science and Technology, Trondheim, Norway. <https://doi.org/10.5281/zenodo.10701706>
- Walker, T.R. & Fequet, L. 2023. Current trends of unsustainable plastic production and micro(nano)plastic pollution. *TrAC Trends in Analytical Chemistry*, 160: 116984. <https://doi.org/10.1016/j.trac.2023.116984>
- Weinrich, R. & Herbes, C. 2023. Consumer research on bioplastics: A systematic review. *Q Open*, 3(1): qoad013. <https://doi.org/10.1093/qopen/qoad013>
- WHO (World Health Organization). 2022. Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health. Geneva: World Health Organization. ISBN: 978-92-4-005460-8. <https://www.who.int/publications/i/item/9789240054608>
- Widén, H., Leufvén, A. & Nielsen, T. 2005. Identification of chemicals, possibly originating from misuse of refillable PET bottles, responsible for consumer complaints about off-odours in water and soft drinks. *Food Additives & Contaminants*, 22: 681–692. <https://doi.org/10.1080/02652030500159987>
- Wiesinger, H., Shalin, A., Huang, X., Siegrist, A., Plinke, N., Hellweg, S. & Wang, Z. 2024. LitChemPlast: An Open Database of Chemicals Measured in Plastics. *Environmental Science & Technology Letters*, 11(11): 1147–1160. <https://doi.org/10.1021/acs.estlett.4c00355>

- Wikström, F., Verghese, K., Auras, R., Olsson, A., Williams, H., Wever, R., Grönman, K., Pettersen, M.K., Møller, H. & Soukka, R. 2018. Packaging strategies that save food: a research agenda for 2030. *Journal of Industrial Ecology*, 23(3): 532–540. <https://doi.org/10.1111/jiec.12769>
- Wikström, F., Williams, H., Trischler, J. & Rowe, Z. 2019. The importance of packaging functions for food waste of different products in households. *Sustainability*, 11(9): 2641. <https://doi.org/10.3390/su11092641>
- Yang, Y., Xie, E., Du, Z., Peng, Z., Han, Z., Li, L., Zhao, R. *et al.* 2023. Detection of Various Microplastics in Patients Undergoing Cardiac Surgery. *Environmental Science & Technology*, 57(30): 10911–10918. <https://doi.org/10.1021/acs.est.2c07179>
- Zhang, Q., Huo, Y., Yang, Q., Zhao, F., Li, M. & Ju, J. 2025. Migration of chemical substances from packaging materials to food. *Food Chemistry*, 485: 144544. <https://doi.org/10.1016/j.foodchem.2025.144544>
- Zhang, Y., Pu, S., Lv, X., Gao, Y. & Ge, L. 2020. Global trends and prospects in microplastics research: A bibliometric analysis. *Journal of Hazardous Materials*, 400: 123110. <https://doi.org/10.1016/j.jhazmat.2020.123110>
- Zhao, L., Hu, B., Xia, Q., Huang, S. & Zhuang, S. 2026. Human Exposure to Microplastics from Food-Contact and Daily-Contact Materials: Current Evidence and Perspectives. *Environmental and Microbial Technology*, 1(1): 4. <https://doi.org/10.53941/emt.2026.100004>
- Zimmermann, L., Geueke, B., Parkinson, L.V., Schür, C., Wagner, M. & Muncke, J. 2025. Food contact articles as source of micro- and nanoplastics: a systematic evidence map. *npj Science of Food*, 9(1): 111. <https://doi.org/10.1038/s41538-025-00470-3>
- Zubair, M. & Ullah, A. 2020. Recent advances in protein derived bionanocomposites for food packaging applications. *Critical Reviews in Food Science and Nutrition*, 60(3): 406–434. <https://doi.org/10.1080/10408398.2018.1534800>

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FOOD SAFETY IMPLICATIONS OF RECYCLED PLASTICS AND ALTERNATIVE FOOD CONTACT MATERIALS

Food contact materials (FCMs) are essential to preserve food quality and reduce food waste, with over two-thirds of all packaging materials produced being used by the food and beverage sector. The widespread use of plastic-based FCMs has fuelled a global plastic waste crisis, driven by low recycling rates and uncontrolled or unregulated disposal. As sustainability efforts accelerate, recycled plastics and alternative materials are gaining attention; however, their use in food packaging raises critical food safety questions.

This report examines key food safety considerations for recycled FCMs. It highlights the chemical risks associated with recycled plastics, including contaminants migration, intentionally and non-intentionally added substances and unknown compounds. Beyond chemical migration, emerging concerns, such as micro- and nanoplastics in food, further complicate regulatory decision-making. The document also explores potential food safety issues related to bioplastics and smart packaging – innovations that help achieve sustainability and improve functionality but introduce new safety considerations tied to feedstock properties and added chemicals.

Closing data gaps on the identification of migrating contaminants, developing realistic chemical exposure scenarios for FCMs use building traceability systems, and harmonizing global regulatory frameworks specific to recycled FCMs and bio-based alternatives will assist in developing a sound scientific risk assessment process, keep pace with innovation and help in meeting existing and future global plastic waste reduction targets.

The authors trust that this report provides relevant information to support the development of international guidance on food safety aspects of recycled plastics and FCMs made from renewable resources.

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