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Attending to food, consumer, manufacturer, and environmental issues

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Food packaging technology considerations for designers: Attending to food, consumer, manufacturer, and environmental issues

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Abstract

Food packaging is essential for preserving food safety and quality while also addressing environmental concerns. Designers are at the forefront of developing packaging solutions that not only meet functional requirements but also align with evolving consumer preferences and sustainability concerns. To inform designers, this paper discusses fundamental principles of food packaging technology, encompassing aspects such as food preservation, distribution, marketing, usability, and disposal. It provides examples of innovations in active and smart packaging, nanotechnology, material biodegradability, and recyclability, as well as strategies to reduce packaging waste. By providing future food packaging designers with this essential knowledge and these insights, we hope to encourage them to contribute to future innovations that meet the needs of consumers and the environment.

KEYWORDS

consumer, food waste, packaging design, sustainability, usability

1 | INTRODUCTION

The food industry is the largest user of packaging at the consumer level (Saha et al., 2022). However, any desire to reduce packaging costs in the supply chain must be carefully balanced against the fundamental technical requirements for food safety and integrity, while also ensuring efficient logistics services. The choice of suitable packaging is essential in preventing food waste and involves many considerations regarding required strength, barrier properties, shape, size, usability, standing out on supermarket shelves, and so on. The importance of good package functionality has also increased in recent years with the proliferation of e-commerce and the long shipping window (Coles et al., 2003). In addition, value can be added to packaging for marketing purposes: Food companies have recognized the importance of innovative packaging design as a competitive element that can support brand identity (Simms & Trott, 2022). Regarding the different packaging aspects that designers may change, we can distinguish between the choice of packaging materials, the choice of dimensions (shape, size, thickness), packaging functionalities (opening and closing, grip), and graphics (brands, labels, information).

The evolution of food packaging parallels the progress of human society. From the early days of agriculture, where storage techniques were devised to preserve harvest surpluses, to the complexities of modern trade and

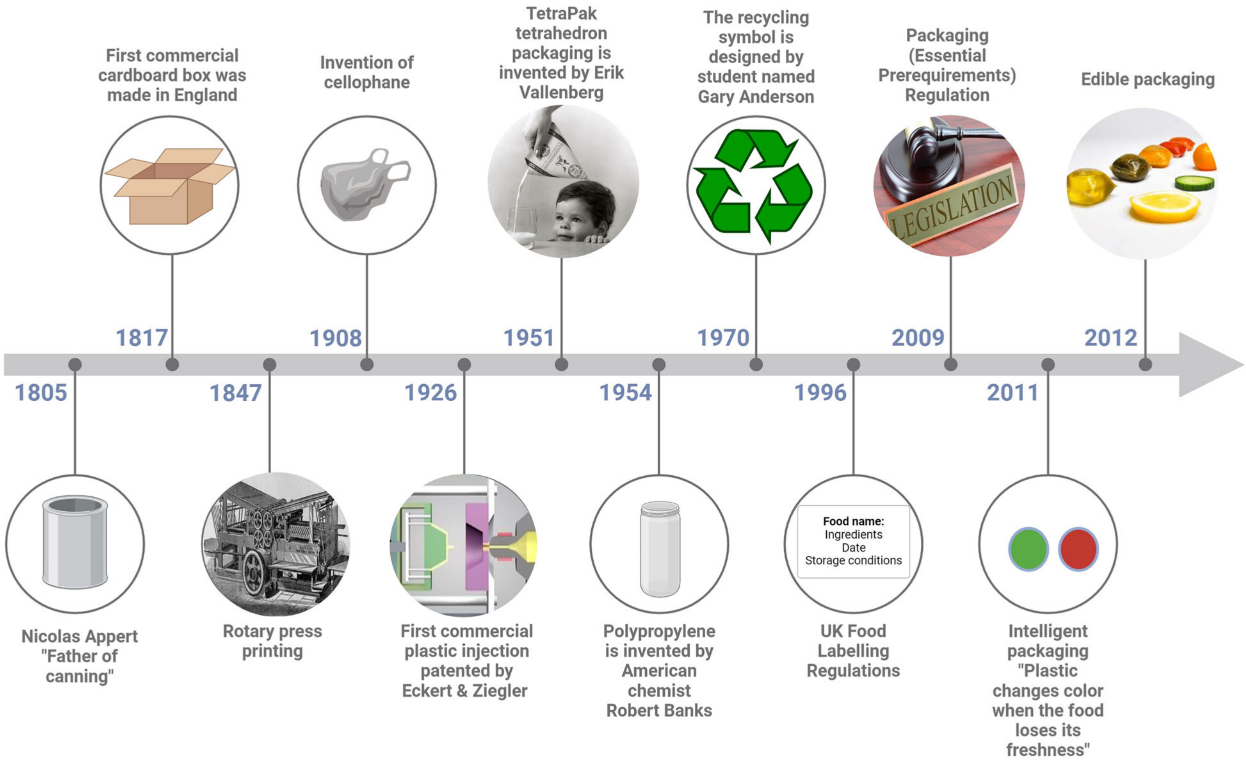

FIGURE 1 Brief history of packaging design (figure generated with BioRender [https://biorender.com/]).

food security concerns, packaging has adapted to meet the needs of the times (Bopp, 2019). Figure 1 shows a brief history of the evolution of food packaging. The Industrial Revolution introduced new manufacturing methods and materials, repurposed for food packaging, notably metal cans by Nicolas Appert for food preservation. Paperboard emerged in the early 1800s, followed by innovations like Tetra Pak's laminated packaging in 1951, enhancing shelf life without high heat stress. Oriented polypropylene (OPP), developed in 1954, improved moisture barrier, clarity, and stiffness and is widely used in snack food overwraps (Risch, 2009). In recent years, addressing sustainability challenges has become crucial. Notably, keywords like active and smart packaging and edible films have gained significant attention (Akin et al., 2023).

Designers are trained to integrate information from different disciplines. Hence, they are equipped to balance food safety requirements with material and manufacturing challenges, marketing wishes, end-user requirements, and environmental impact. Because designers tend to broaden perspectives on topics of interest, are skilled in facilitating collaboration between experts, and engage different types of stakeholders in the design process (Schifferstein, 2016), they can come up with new types of solutions where disciplinary approaches get stuck. However, the field of food packaging design has its own intricacies, and to prepare industrial designers for working in this field, they must have an overview of the basic principles that govern its main challenges.

In this paper, we describe the different roles that packaging technology plays in the development of products for the food industry. Unlike other packaging technology reviews, our review is specifically aimed at industrial designers with a general design education who are not specifically trained in developing food packaging. By covering the most important technological aspects, we aim to provide future food packaging designers with the essential background knowledge to contribute to innovations in this challenging field. Therefore, we provide a broad overview of basic principles and interesting developments in different areas, without going into too much detail.

To structure our discussion, we will focus on the key packaging needs and concerns of three stakeholders at different levels of complexity: (1) consumers who purchase, prepare, eat, and dispose of food products, (2) businesses that produce, transport, store, distribute, and sell food products, and (3) society at large, which is keen to provide people with safe, affordable, and nutritious foods but is also concerned about the impact of packaging production and waste on the environment. We structure the discussion by focusing on six main functions that need to be considered: ensuring food safety and preserving food quality, conveying product information, ease of use for the consumer, fitting into the manufacturing process, ease of handling during logistic operations, and minimal impact on the environment. To stimulate the creativity of designers and develop a forward-looking perspective, we include examples of recent technological developments in our discussion.

2 | ENSURE FOOD SAFETY AND PRESERVE QUALITY

A primary function of food packaging is to maintain the quality of the food over time. Consumers want the packaging to ensure the product is safe to eat, as well as to retain its properties, like flavor, nutritional value, texture, color, and so on. Similarly, businesses make it their priority to preserve quality, so that the products contribute positively to the brand and company reputation. And for society, it is important that people have access to safe and nutritious food.

One of the primary considerations for designers is the selection of materials that ensure product integrity, safety, and sustainability. Understanding the product's characteristics such as its physical nature (gaseous, granules, powders, emulsions, paste), chemical or biochemical nature (ingredients, nutritional value, volatile substances), dimensions (size and shape), volume, weight, and susceptibility to damage is crucial for designing suitable packaging. Packaging needs to protect against chemical changes (e.g., staling of bread), biochemical changes (e.g., enzymatic respiration of fruits and vegetables), and microbial spoilage (Coles et al., 2003; Robertson, 2009), as well as external factors like light, heat, and water.

Different food products and storage conditions require specific packaging considerations (Table 1). For example, highly perishable strawberries require precise packaging solutions to maintain quality from farm to consumer. Effective ventilation in trays significantly accelerates cooling and reduces condensation risk by up to 45%. Optimal designs balance vent size (5–12 mm), their even distribution, and total opening area (5.5%–7%) to minimize losses while ensuring longer shelf life (Tobler et al., 2024). Understanding the migration of volatile substances between packaging and its contents is crucial for determining the shelf life of food. Desorption kinetics, influenced by substance properties and environmental factors like temperature and relative humidity, can be modeled using pseudo-first-order kinetics, which quantitatively predicts the time scale of the release of volatile organic compounds (Serebrennikova et al., 2024).

Effective humidity control is important for maintaining product quality, stability, and shelf life. Special designs incorporating enhanced ventilation, absorbent pads or humidity-regulating trays (especially for fresh produce, meat, or fish), and techniques like active packaging or modified atmosphere packaging (MAP) play a vital role in minimizing risks associated with spoilage. Packaging with advanced moisture adsorbents, like silica gel, activated carbon, and zeolites, can protect food from moisture-related deterioration. Aptar's 3-Phase Activ-Polymer technology integrates nanoporous materials into composite polymers to enhance physical properties and moisture adsorption, ensuring better protection and extending the shelf life of food products (Daou, 2024). Moreover, there are new developments in film materials, such as the use of a bionic feather-like barbed texture in carboxymethyl cellulose/polyvinyl alcohol-based packaging, giving them superior hydrophobicity and water vapor barrier properties. Its structural integrity, biodegradability, and functional additives like quercetin provide UV shielding, antimicrobial effects, and real-time food spoilage monitoring. The novel film extends food shelf life by 5 days, outperforming polyethylene (PE) packaging by 2 days, while advancing sustainable packaging design capabilities (Jiang et al., 2024).

Among *active packaging*, there are self-cooling packages for beer and soft drinks (Garcia-Oliveira et al., 2022) and self-heating packages for chocolate, soup, and coffee (Henriques, 2022). For fresh fruit and vegetables, there are packages with polymers that can adjust their permeability to gases such as oxygen, carbon dioxide, and water vapor depending on the temperature (Robertson, 2009; Turan et al., 2016, 2017). Incorporating antimicrobials in packaging materials stands as a promising active packaging innovation to enhance food safety and prolong shelf life (Manzoor et al., 2023). Possibly, natural sources like mustard seeds may be incorporated in the design of the packaging system for milk, fish, and meat products: Allyl isothiocyanate released from ground mustard seeds in packaging headspace and liquid medium may inhibit spoilage bacteria growth in packaged food products (Bahmid et al., 2020). Carbon dots (CDs) can be integrated into food packaging to develop biodegradable, antibacterial, UV-resistant, and antioxidant films (Gupta et al., 2023). Moreover, halloysite nanotube, a unique alumina silicate-based nanoclay with a hollow tubular structure, demonstrates antimicrobial, antioxidant, and antifungal activities (Deshmukh et al., 2023). In the European Union, regulations exist to outline general food contact material requirements (European Parliament, 2004), as well as specific rules for active and smart materials, enforcing compliance with safety standards (European Commission, 2009).

Modified atmosphere packaging involves removing the air from the packaging and replacing it with a specific gas or gas mixture, usually nitrogen and carbon dioxide (Czerwiński et al., 2021). When selecting packaging films, the gas permeability, water vapor transmission rate, mechanical properties, transparency, type of packaging, and sealing

TABLE 1 Food product needs in terms of packaging (Robertson, 2009).

Product	Shelf life affected by	Barrier against			
		Light	O_2	H_2O	Odor
Flesh foods	Biochemical reactions, e.g., lipid oxidation, discoloration, microbial spoilage, softening, odor	×	×		×
Horticultural products	Biochemical reactions, e.g., respiration, transpiration, ethylene autocatalysis, condensation, enzymatic and microbial proliferation	×	×	×	
Dairy products	Off-flavors, enzymatic and microbial deteriorations, lipid oxidation, nonenzymatic browning, caking of powders	×	×	×	×
Cereal, snack foods, confectionary	Hydrolysis from enzyme, lipid oxidation, rancid off-flavor, moisture gain, loss of, e.g., crispness, vitamin loss, mechanical damage (e.g., breakage), softening, or caking, aroma loss, color fading, sugar bloom, fat bloom (chocolate), microbial spoilage	×	×	×	×
Bakery products	Microbial spoilage, staling, moisture loss/gain, softening of the crust and drying of the crumb, rancidity, starch retrogradation/staling, microbial spoilage	×	×	×	
Beverages	Microbial growth, loss of carbonation for carbonated beverages, oxidation or acid hydrolysis of oils and colorings	×	×		
Coffee	Staling, caking, loss of CO_2 and oxidative degradation of coffee aroma		×	×	×

reliability are the most important characteristics to consider. Some fresh food products, like fruits and vegetables, are breathing products, and it is necessary to allow gases to pass through the film. Films designed with these properties are called permeable films. Other films, called barrier films, are designed to prevent the exchange of gases.

When designing materials and components that may come into contact with food, such as packaging materials and smart packaging components, it is important to consider the potential effects of food–material interactions. Packaging design guidelines for food contact materials are critical to ensuring safety, quality, and regulatory compliance (European Parliament, 2004). While selecting a packaging material or component, designers should be aware that packaging components can leak into the food product and vice versa, which could reduce food quality (e.g., taste defects) or have health implications. Different foods (e.g., acidic, fatty, dry) interact differently with packaging materials and components. Therefore, designers must select materials that are compatible with the specific type of food while also keeping in mind the conditions of processing and use throughout the packaging's life cycle. For example, materials and components must be able to withstand the temperatures to which they are exposed, such as during (hot)filling in production facilities or freezing and microwaving at home (Hotchkiss, 1997). Migration testing is performed during the packaging development process to ensure that chemicals from the packaging do not migrate into the food at unsafe levels. Examples of substances that may be harmful include residual monomers and plasticizers (see Appendix).

In addition to the food–material interaction, permeability to volatiles and cross-contaminations can also compromise food quality. This can occur, for example, if a food product is stored in an environment with a strong odor. In that case, the volatiles in the air may penetrate the packaging material, which can lead to sensory defects in the food product. This can happen, for instance, in supermarkets when food packages are stored next to herbs and spices that are sold unpackaged or next to care products or detergents with a distinct odor. Therefore, designers should ensure that packaging materials have low permeability to volatile compounds to avoid contamination by external odors. By addressing these considerations, manufacturers can further ensure that their packaging not only protects food safety and quality but also maintains the integrity of the food's sensory properties even in challenging storage environments.

3 | PRODUCT INFORMATION

Packages need to identify the product and its manufacturer, as well as provide instructions for handling and storage. Consumer food packages contain an expiration date, product use instructions, and nutrition information (European Union, 2011). A product brand may provide a feeling of familiarity or trust. In addition, packages may provide information on which packaging materials have been used, whether the packages are part of a deposit system, and how the packages may be recycled or disposed of.

FIGURE 2 Iconic packaging designs: The Coca-Cola bottle, Heinz ketchup, Maille mustard, and Marmite.

For presentation in the retail environment, it is important that primary packages are attractive to consumers. The package should not only look good, but it should also attract consumers' attention among many other products on the shelves and communicate the product's benefits in an appealing way (Garber et al., 2008). An important element in its communication is the role of the brand, as the brand image may function as a sign of quality (Aaker, 1995). To show the power of branding, Coca-Cola's classic contoured glass bottle, designed in 1915, revolutionized brand recognition. The iconic shape stands out, staying recognizable over the years, and currently fostering a sense of nostalgia and enhancing the overall Coke experience (Figure 2). This showcases the power of packaging design in establishing an emotional bond with consumers, reinforcing brand identity, and encouraging loyalty (Partners + Hunt, 2023). As the Coca-Cola example shows, product branding is not only communicated through the package's graphic design but may also involve choices for specific materials and dimensions (shape, size, weight).

To increase flexibility and quickly adapt graphic designs to market trends, companies can now make use of digital printing techniques. Digital printing makes it possible to create many varieties on one package, as each package can be printed from a different, personalized source file. It ensures cost-efficiency, faster production, and superior quality, aligning with sustainability goals and catering to consumer preferences. While a graphic design agency may be responsible for the branding and imagery, the structural designer is responsible for the 3D package, including the logos and symbols the package needs to carry for legal reasons. For example, Packforward (2023) provides an overview of the logos that are used in different EU countries to indicate how packages should be disposed of, while KIDV (2021) provides a more elaborate overview covering certification marks and recycling and disposal symbols that are used in the Netherlands.

By incorporating interactive elements like augmented reality labels and smart packaging that utilizes sensors and digital systems, consumers can obtain valuable information about product origins, real-time quality during transportation and storage, and usage instructions (Palazzo et al., 2023). For instance, on-pack visual indicators have been developed for real-time monitoring of raw beef steaks in modified atmosphere packaging. Three pH-sensitive paper indicators can accurately show beef spoilage with color changes (Bhadury et al., 2024). In addition, QR codes or barcodes integrated into food packaging to display the food's history are gaining interest (Kaliaraj et al., 2023). Smart tags enhance consumer confidence by providing data on product quality, shelf life, and nutritional value. QR codes and contactless delivery systems further improve the consumer experience and align with sustainable design principles (Bumbudsanpharoke & Ko, 2022; Rotsios et al., 2022) (Figure 3). As consumers are often confused by the current use of "best before," "use by," and other date labels printed on packaging (Patra et al., 2022), challenges involve aligning evolving consumer expectations with regulatory compliance, integrating user-friendly interfaces, and leveraging emerging technologies to enhance value in the food industry (Htun et al., 2023).

4 | CONSUMER USABILITY

Designers must create packaging that enhances the user experience while maintaining product freshness and safety. For consumers, this implies easy acquisition, transport, storage, usage, and disposal. Packages should be easy to open and close, provide enough grip for handling, be appropriately sized, and so on. As the population ages, packaging design must consider decreased strength and dexterity of the population.

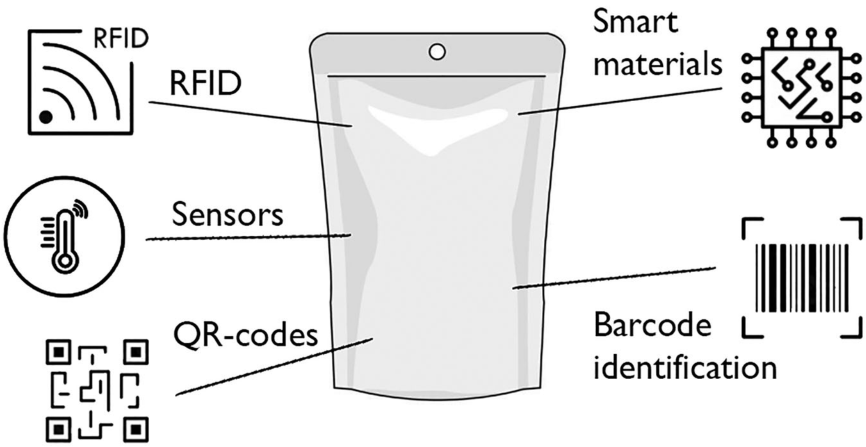

FIGURE 3 Digitalization will take smart food packaging to the next level (adapted from Valtokari, 2021).

Understanding how consumers manipulate packaging can guide designers in creating more accessible packaging. Consumers appreciate packaging that is easy to open without requiring excessive force. Designers should ensure that seals are strong enough to maintain product freshness while also being easy to open. For instance, Rowson and Yoxall (2011) found that female consumers primarily use a spherical grip, generating lower torque than men. Other factors affecting grip effectiveness include wrist strength, friction with the container, and container diameter. Improving accessibility involves considering closure diameter and enhancing friction between the hand and the jar lid (Figure 4).

Packaging stability is also an important factor in preventing accidents during product usage. For instance, tall, narrow containers with rounded bases for soups were found to be prone to tipping over, which could lead to spills and burn injuries. Redesigning packaging with a wider base and shorter height, along with clear warnings, could significantly reduce the number of soup-related burns (Greenhalgh et al., 2006).

Pack size, shape, and user-friendliness (e.g., easy opening, efficient emptying) have a large effect on the amount of household food waste generated (Wikström, Williams, et al., 2019). A recent systematic review analyzed 43 academic and industry studies from 2006 to 2020 across multiple countries and identified packaging-related drivers and solutions for household food waste across 28 food categories (Chan, 2022). The study found that optimized portioning, easy-to-empty designs, resealability, clear on-pack communication, and accurate storage instructions can help prevent food waste. Certain food groups like bread, dairy, fish, and fresh produce offer strategic opportunities for enhanced packaging solutions (Figure 5). These consumer insights provide opportunities for food and beverage brands worldwide to tweak packaging designs, reduce waste, and improve sustainability (Chan, 2022).

Proper seals should allow for easy opening while also preventing leakage and contamination, and they should maintain the desired environment inside the package when closed (Ilhan et al., 2021). Packaging designers should be familiar with different sealing methods and closures, for example, roll-on tamper-evident closures for glass/plastic containers, heat sealing, peelable seals, and cold seals (Robertson, 2009), to select the right one. Heat sealing bonds thermoplastics, while peelable and cold seals are easy to open (Ilhan et al., 2021). To achieve optimal peel seals, designers must pay attention to details such as properly aligning sealant layers and using flexible sealing jaws to apply even pressure, particularly on irregular surfaces (Ilhan et al., 2021). Easy opening of heat-sealable food packaging requires a delicate balance of peel strength: It must be strong enough to prevent opening during storage and handling under varying environmental temperatures, yet weak enough to be opened by people with limited muscle strength (Bamps et al., 2021). Therefore, packaging designers must carefully choose adhesive materials with robust bonding properties to prevent adhesive failure so that the seals maintain their integrity during handling and storage. Additionally, they should prioritize sealant materials with adequate cohesion to withstand the stresses encountered during handling and opening without disintegration. Furthermore, designers should opt for sealing methods and materials that limit the risk of delamination, which can be achieved by optimizing sealing parameters and selecting materials that are compatible with each other (Figure 6).

Seals also function as tamper-evident features. Tamper evidence refers to any packaging feature that provides clear visual, auditory, or tactile evidence that a product has been opened or altered. This can include color changes, broken seals, or misaligned parts. Tamper evidence helps protect the integrity of the product and ensures that the product is safe and has not been compromised. In many industries, especially food, beverages, and

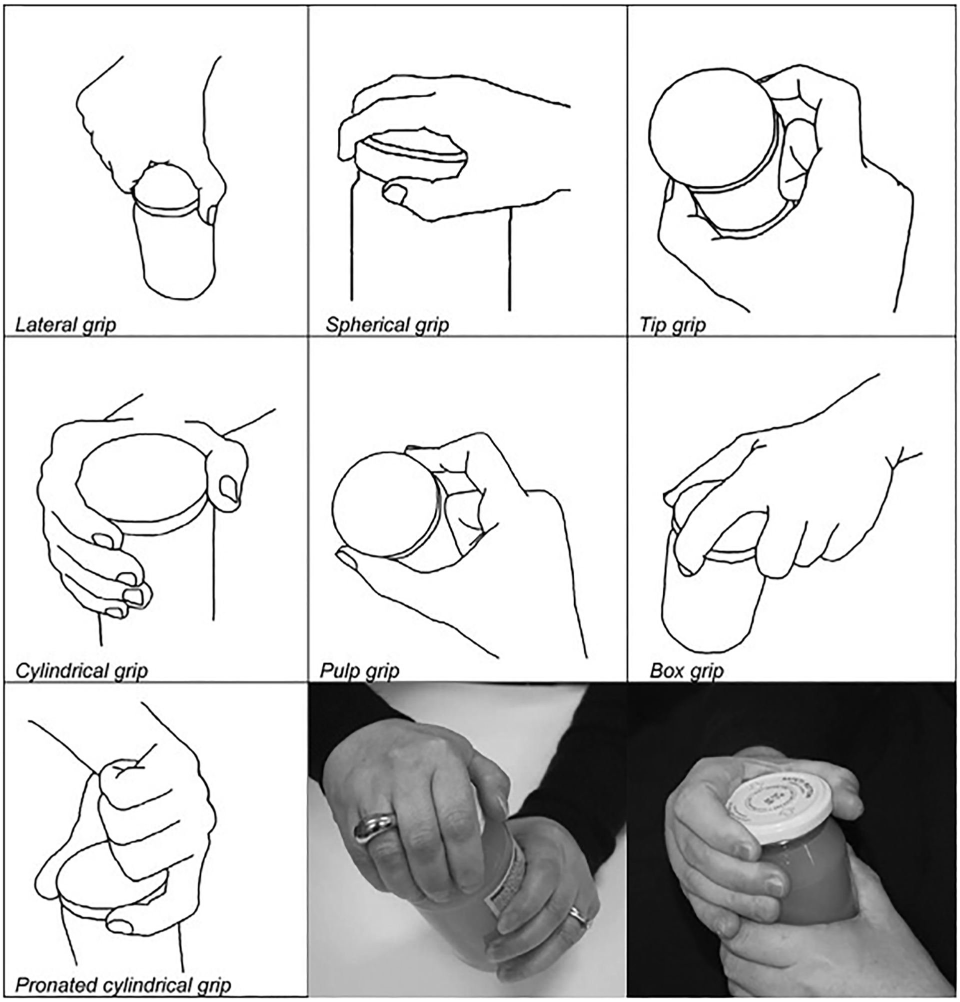

FIGURE 4 Typical grips used when manipulating packaging. Left photo: Typical spherical grip used by female participants. Right photo: Typical cylindrical grip used by male participants (reprinted by permission from Rowson & Yoxall, 2011).

pharmaceuticals, tamper-evident packaging is legally required to meet safety standards. Common types of tamper-evident features include (Figure 7):

- Sealed caps: a ring around the neck of a beverage bottle that breaks when opened.
- Shrink bands: clear or printed plastic films around caps or lids that must be torn or cut.
- Breakable seals: foil or paper seals placed under caps or over container openings that must be removed or punctured.
- Pop-up indicators: lids or caps that change appearance when the vacuum is broken (e.g., a "popped" button on a glass jar lid).
- Film wraps: flexible films that are wrapped around the product or box and tear when opened.

Packaging designers must understand closures and sealing methods to ensure both security and consumer usability (Theobald, 2012). They must also integrate them seamlessly with the overall branding and packaging aesthetic to maintain a cohesive look. Tamper-evident features should be clear, effective, and easy to open, but this is not always the case. For instance, shrink seals may go unnoticed until opening and can be difficult to open. Tamper-evident features also come with additional costs and often require an extra layer of material. Therefore, creating a tamper-evident solution can be a multifaceted challenge, balancing cost, safety, usability, aesthetics, and compliance with industry standards and sustainability requirements to create functional and trustworthy products.

5 | MANUFACTURING DEMANDS

When designing packaging for a specific food product, requirements determined by the production and filling process must be considered. The need to align packaging

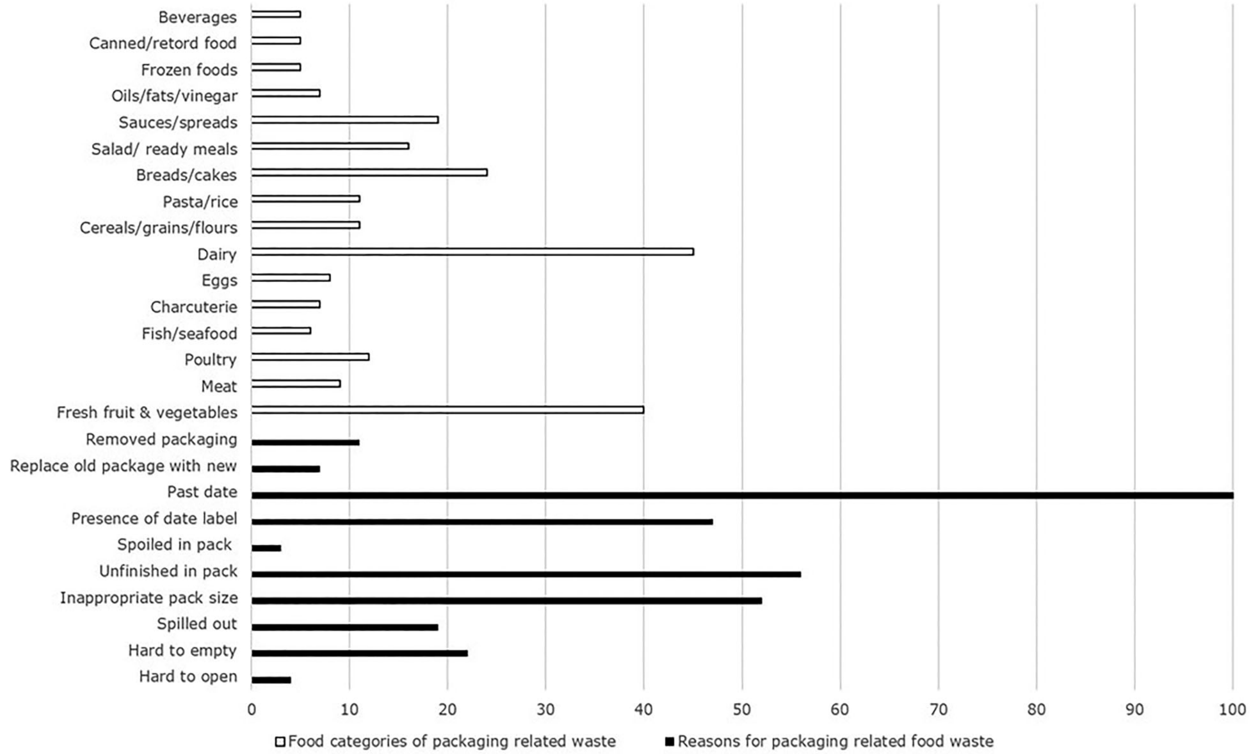

FIGURE 5 Reasons for food waste by food categories and packaging across the globe (based on Chan, 2022).

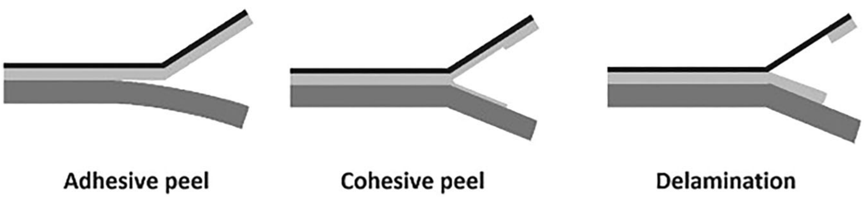

FIGURE 6 Seal separation modes (ASTM, 2023).

FIGURE 7 Examples of tamper evidence features: Breakable opening on tube, breakable seal on cap, pop-up indicator on glass jar, sealed cap, sealed cap with tear strip, and breakable seal on carton.

design, machinery, and production and filling processes concerns the compatibility of the packaging material with the food processing method (e.g., retort sterilization, hot filling, aseptic filling, freezing, modified atmosphere gas flushing, vacuumizing; see Table 2), filling, closing performance, and palletization. Often, opportunities for packaging improvement can be found within the limitations of the machinery, because adjusting machinery to a new packaging design can require huge investments. Packages optimized for the production and filling process can result in less waste, lower production costs, and a streamlined manufacturing process.

The Appendix contains a table that indicates whether a certain packaging material is suitable for a food product, taking into account its compatibility with both the food properties and the manufacturing processes. Designers can use the Appendix table to select suitable packaging materials for specific food products by cross-referencing

TABLE 2 Implications of different food treatments on packaging design.

Treatment	Description	Impact on packaging design
Aseptic packaging	Sterilized food products are filled into packaging (sterilized, e.g., by heat, hydrogen peroxide) in a sterile environment, preventing contamination and extending shelf life without refrigeration.	Requires packaging materials and equipment suitable for maintaining sterility. Packaging materials must withstand sterilization processes without compromising integrity.
Modified atmosphere packaging (gas flushing)	The atmosphere inside the packaging is replaced with a gas mixture that inhibits microbial growth and oxidation, extending shelf life.	Packaging must have gas barrier properties and be compatible with gas-flushing equipment.
Retorting	Food in heat-resistant packaging is sterilized by subjecting it to high temperatures in a retort, destroying harmful bacteria and extending shelf life.	Requires packaging materials capable of withstanding high temperatures and pressure.
Hot-fill	Food or beverage products are heated and filled into containers while hot, destroying microorganisms, preventing recontamination, and extending shelf life.	Packaging materials must withstand high temperatures without deformation or compromise.
In-package pasteurization	Food products are heated to a specific temperature for a set period to kill harmful bacteria and enzymes, extending shelf life while preserving flavor; widely used method for ready-to-eat foods.	Packaging must be suitable for heat treatment and maintain product freshness postpasteurization.
High-pressure processing (HPP)	Food products are subjected to high pressure to inactivate spoilage microorganisms.	Packaging materials must withstand high pressure without compromise.
Vacuum packaging	Air is removed from packaging to inhibit the growth of aerobic microorganisms.	Requires packaging materials capable of maintaining a vacuum seal.
Active packaging	Packaging involves incorporating antimicrobial, antioxidant substances into packaging materials that interact with the packaged food.	Packaging design must accommodate the incorporation of these active substances and ensure their effectiveness throughout the product's lifespan.
Smart packaging	Packaging incorporates sensors, time–temperature indicators, or RFID tags to monitor the condition of the food and provide information to consumers or producers.	Packaging design must integrate these technologies while maintaining sustainability, product integrity, and functionality of the packaging.

the properties of the food and the manufacturing processes involved. For instance, depending on whether the food product requires moisture resistance, temperature stability, or barrier properties, designers can review the material properties of options like polyolefins, which are commonly used for their flexibility, moisture barrier properties, and heat sealability, making them ideal for foods that require durable, moisture-resistant packaging (Morris, 2024). Copolymers of ethylene like ethylene-vinyl alcohol are used for their excellent barrier properties, especially against oxygen and moisture, which improves food preservation and is ideal for foods that require protection from oxygen or chemical degradation (Maes et al., 2018). Substituted olefins like polystyrene provide clarity and stiffness, making them suitable for dry foods or foods that need to be visible in their packaging (Muthukumar et al., 2024). Polyesters like polyethylene terephthalate (PET) are stable at high temperatures and have good gas barrier properties, making them suitable for packaging beverages or perishable foods (Sarda et al., 2022). Polyamides are excellent for foods that require strong barrier properties and resistance to abrasion during transportation, such as vacuum-sealed or frozen products (Marangoni Júnior et al., 2023). Paper is a renewable, biodegradable option for dry foods, but it generally requires coatings to improve barrier properties (Kunam et al., 2024).

Designers should be aware that considering food–package–processing relationships may also have implications for the migration of packaging material components. For instance, polyamide is used in multilayer films as a gas barrier layer for packaging vegetables, meat, and cheese. However, the monomer conversion is less than 100%, and the residual monomer can migrate to food from the packaging. Hence, attention should be paid to monomer migration for food–packaging systems involving conventional thermal processes (pasteurization and sterilization) or new processing technologies (microwave-assisted thermal sterilization, high-pressure processing, ultrasound, and so on). Apparently, ultrasonic processing of packaging materials shows minimal migration of hexamethylenediamine and ε-caprolactam monomers, which complies with EU safety limits. Tests with multilayer polyethylene/polyamide packages in various food simulants confirmed that ultrasound did not compromise food safety (Marangoni Júnior et al., 2024).

Most packaging operations in food manufacturing are automatic or semiautomatic and often involve high-speed operations. The main difference between a packaging machine and a filling machine is that a packaging machine creates a package for a product, while a filling machine only fills containers with a product. Filling machines use methods such as gravity filling, vacuum filling, and piston filling based on volume and auger, or agitator filling based on weight to fill containers. The containers must be of specified dimensions, type, and format to run on filling lines. Packaging operations typically involve form–fill–seal methods, implying that the machine forms a package, fills the package with a food product, and then seals the package. Other common forms of packaging operations include skin packaging (a product is placed on a tray and a thin sheet of transparent plastic is placed over the product, usually with a heat-seal coating) and shrink packaging (a polymer plastic film is placed over a product and shrinks tightly when heat is applied) (Coles et al., 2003; Robertson, 2009). Specific innovations in this domain can offer substantial benefits, such as the CRYOVAC mono-PET roll stock film, which offers tamper-evident, recyclable packaging with a vacuum skin for lamb cutlets, extending shelf life to 18 days (AIPIA, 2024).

6 | LOGISTIC DEMANDS

Packaging is part of a coordinated system for preparing goods for transportation, distribution, storage, retail, and end use through safe delivery at minimal cost (Morris, 2022). Besides containment and protection, it is used to unite and allocate products. To allow efficient logistics and transportation, it should provide relevant information and enable convenient handling (Sohrabpour et al., 2016). Figure 8 illustrates the ecosystem involved in food distribution flows from farm to the retailer/consumer. The food supply chain connects the players involved in the various activities in the chain such as procurement, production, transportation, processing, distribution, consumption, and disposal. The food that consumers buy has usually passed through various steps, including raw material processing, safety standards check, packing, transportation, and other value-adding processes (European Commission, 2015). Designing packaging with optimal dimensions, materials, ease of production, ease of use, and limited impact on the environment forms the main design challenges (Sarghini et al., 2019). Packaging that is stackable, easy to handle, and takes up minimal space in storage and transportation contributes to a more efficient supply chain.

It is important to realize that supply chain characteristics can vary greatly from food product to food product, depending on the type of product, operations that need to be carried out during food processing, and the sales channels (Figure 8). As a result, lead times from production to consumer can vary significantly: While fresh food can go from “farm” to “fork” in just a few days, processed food can take months to reach consumers’ plates (Schonberger, 2019). These lead times have consequences for the development of appropriate packaging, especially for

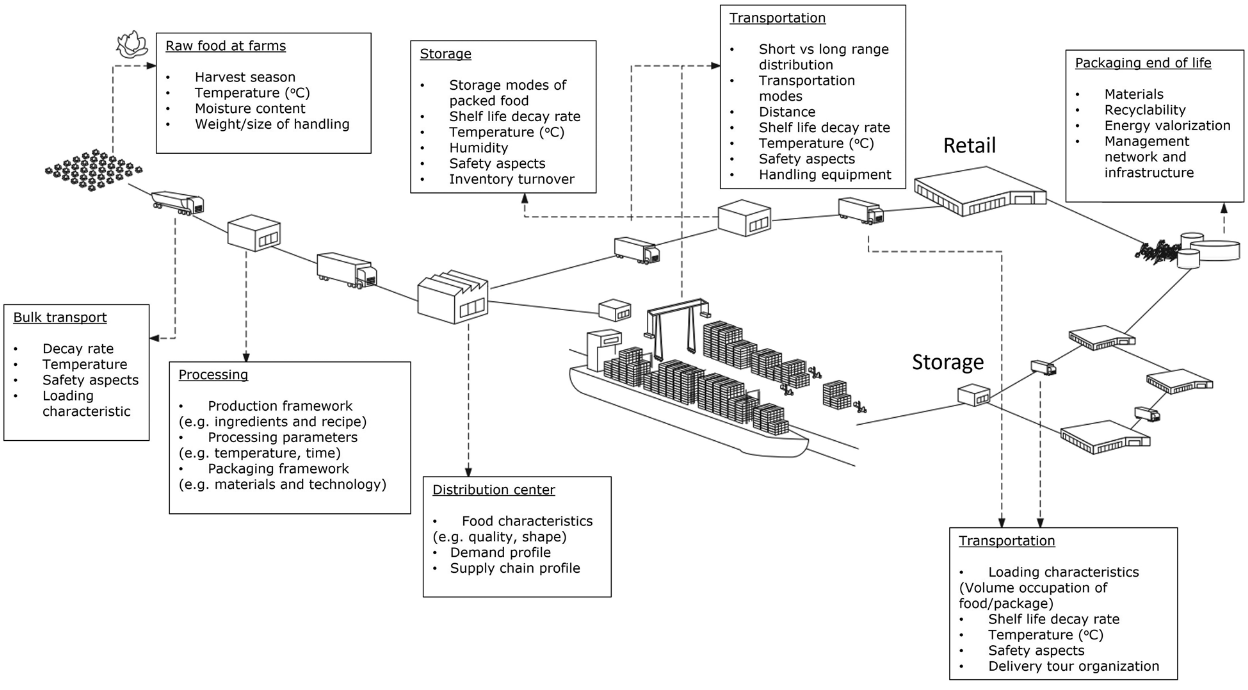

FIGURE 8 Aspects of food packaging design along the food supply chain (adapted from Sarghini et al., 2019).

processed food. Packaging must protect the food during the entire shelf life of the product. This includes the lead time in the supply chain, but also during storage and transport, where conditions may vary greatly. Producers can perform tests and trials, including simulations on physical and virtual prototypes, to study the effect of lead times and specific storage and transport conditions on the quality of the product and on food-packaging interactions (Accorsi et al., 2022; Ambaw et al., 2022).

A distinction is usually made between the different levels of packaging. *Primary packaging* refers to the packaging that is in direct contact with the enclosed product. It forms the first and the most important protective barrier (Molina-Besch & Palsson, 2016). Primary packaging includes metal cans, paperboard cartons, glass bottles, and plastic pouches. *Secondary packaging*, such as a corrugated case or box, contains several primary packages. It is the physical distribution carrier and is increasingly designed to be used in stores for the display of primary packaging on the shelves (shelf-ready packaging). *Tertiary packaging* contains several secondary packages, for example, a pallet wrapped in stretch film with corrugated cases. In interstate or international trade, *quaternary packaging* is used to facilitate the handling of tertiary packages. This is generally a metal container that can hold many pallets that are transported with giant cranes to or from ships, trains, and flatbed trucks. Certain containers can control temperature, humidity, and/or gas atmosphere, which is necessary for the transportation of frozen foods, chilled meats, and fresh fruit and vegetables. Figure 9 shows a schematic overview illustrating the different hierarchical levels for packaging.

Environmental factors during storage and transport can damage the product due to the presence of gases (particularly oxygen), water and water vapor, light (particularly UV radiation), fluctuations in temperature, and contaminants such as car exhaust, dust, and dirt. Physical damage can occur due to shock from drops and bumps, vibration due to transportation, and air or compression damage arising from stacking during transportation or storage. Biological influences include microorganisms (bacteria, molds, fungi, yeasts, and viruses) and macroorganisms (mites, insects, rodents, and birds) that are ubiquitous in many warehouses and stores (Coles et al., 2003).

Smart packaging can monitor and convey food information across all levels of packaging systems, from primary to tertiary packaging. Data carriers like barcode labels and RFID tags support automated traceability in food supply chains, improving inventory control and product monitoring (Wikström, Verghese, et al., 2019). An interesting example is provided by Coca-Cola and the University of Reading (UK), which use microchipped soft drink containers for refilling at central dispensers and for direct billing (Megale Coelho, Corona, ten Klooster, et al., 2020). Packaging sensors can provide quantitative data on food quality, with research exploring the potential of edible sensors for monitoring fruit ripening. In some cases, food spoilage can be tracked in real time by sensors, captured via a smartphone camera, and evaluated with color recognition software (Jiang et al., 2024). However, concerns remain

FIGURE 9 Schematic overview showing different packaging levels.

about the health risks of integrating sensors into food contact materials, highlighting the need for further research in this area (Cataldi et al., 2022).

7 | ENVIRONMENTAL IMPACT

To fulfill packaging's role in society, it should not only keep food products safe and optimize quality, but the packaging should also not burden the environment. However, food loss and packaging waste are a widespread problem in global food systems. According to the Industry Council for Packaging and the Environment (INCPEN), less than 1% of packaged food is wasted, compared to between 10% and 20% of unpackaged food. Food waste is the third largest source of greenhouse gas emissions, and therefore, there is an intense debate on food safety and sustainable packaging. In this regard, active and smart packaging technologies can save food and help achieve sustainability goals. Despite this, many countries lack food waste reduction targets, and industry stakeholders resist packaging redesign due to cost concerns (AIPIA, 2023). Consumer education about these technologies is critical, as awareness can lead to smarter purchasing decisions and significantly reduce household food waste. For environmentally impactful products like foods, prioritizing smaller package sizes may be the most effective strategy, despite the potential increase in the amount of packaging materials used (Wikström, Verghese, et al., 2019). At the same time, reducing packaging waste is a top priority, with resource efficiency and management being paramount, along with minimizing negative environmental impacts caused by visual pollution and microplastic contamination. In addition, the production of packaging and its raw materials, the packaging process, transportation, and storage in refrigerators all consume significant amounts of energy (Markeviciute & Varzinskas, 2022).

Due to increased consumer awareness about the plastic soup in the oceans, consumers now also require sustainable packages (Coles et al., 2003; Robertson, 2009). Consumer perception of eco-friendliness is mainly determined by the packaging material, and most studies show that consumers perceive glass bottles as the most sustainable, followed by carton packaging and plastic bottles, but unfortunately, this is not in agreement with lifecycle analyses (Nguyen et al., 2020; Steenis et al., 2017). The environmental impact of packaging varies depending on the food–packaging combination. At one end of the spectrum is the packaging for meat or cheese (products with a high indirect climate impact), where the packaging accounts for only 0.5%–3% of the total environmental impact. On the other end are small glass jars of jam or packaged water (products with a low indirect climate impact), where the packaging accounts for nearly 100% of the total environmental impact. On average, packaging determines 10% of the total environmental impact of food–packaging combinations (Milieu Centraal, 2022). However, the packaging makes up a very visible aspect of the supply chain for both consumers and governments. Therefore, it is recommended to make packaging more sustainable both by minimizing the total ecological footprint and by addressing consumer expectations and legislation.

The growing emphasis on sustainability has prompted designers to adopt a holistic approach that considers the entire lifecycle of packaging, from sourcing to disposal. Implementing principles of the circular economy, such as recyclability, reusability, and waste reduction, is paramount in minimizing environmental footprint. Figure 10 shows the mainly linear flow of plastic packaging materials for the world in 2013 (World Economic Forum et al., 2016). In this flow, only 2% of all plastic packaging material was recycled, while most of it was wasted. Although the percentages in the different streams might differ considerably between countries, on average 98% of the raw material for plastic packaging materials in the world was new raw material, mainly from fossil fuels. Most of the plastic packaging ended up in the environment, in landfills, or was incinerated. Of the 14% collected for recycling, another 4% was lost during recycling, while 8% was downcycled into car parts, benches, and so forth

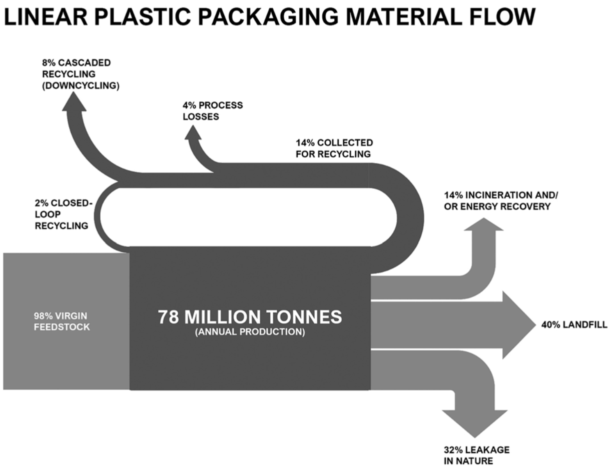

FIGURE 10 Global flows of plastic packaging materials in 2013PET (adapted from World Economic Forum et al., 2016).

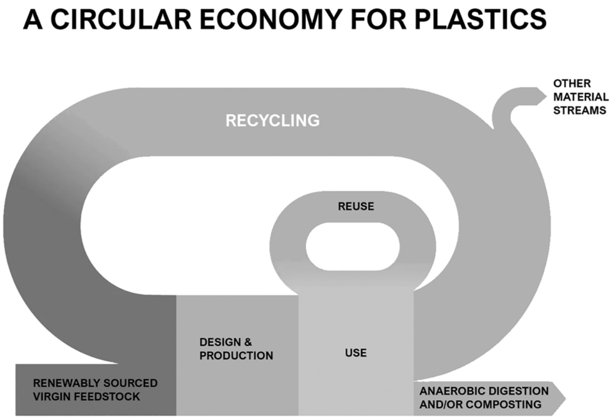

FIGURE 11 Ambitions of the new plastics economy (adapted from World Economic Forum et al., 2016).

because the plastic quality was lower due to contamination with other materials. Only 2% was used for new packaging materials. Therefore, the ambition was set to close the upper loop and stimulate recycling.

The circular economy is a system where materials do not become waste and nature is regenerated. Products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The circular economy tackles climate change and other global challenges, like biodiversity loss and pollution, by decoupling economic activity from the consumption of finite resources (Ellen MacArthur Foundation, 2024). A circular approach requires designers to ask different questions: How can I take the waste phase into account by ensuring that the packaging is easily recyclable? How do I ensure that no waste is created? What other systems or business models can we apply to meet consumer needs?

Figure 11 shows the ambitions of the new plastics economy, in which almost all plastic packaging materials are reused or recycled. This implies that the recycling process must be radically improved, both technically and economically. Reuse can be promoted by implementing more deposit systems and ensuring that packaging is easy to clean and refill. The negative effects of packaging must also be reduced to limit leakage into nature, increase the possibilities for composting, and reduce the amount of plastic that is burned. Furthermore, raw materials should no longer come from fossil fuels but must be replaced by renewable sources.

The circular packaging system diagram, also known as the butterfly diagram, illustrates the continuous flow of materials in a circular (packaging) economy (Figure 12). This diagram shows different stages of the packaging lifecycle and different strategies to close the loop and make the system more sustainable. First, it is possible to reconsider the source material from which the packages are made or to reduce the amount of packaging material being used (see Figure 11). One option is to reuse packages, either by the consumer who washes and refills specific packages (e.g., preservation jars) or by the retailers and producers who collect the used packages, clean them, fill them with new products, and sell them again (e.g., beer bottles). With recycling, the used packaging materials are collected and used as sources of materials for new packages (e.g., beer cans). Another strategy is to recover the energy (e.g., by incineration) or the substances (e.g., by composting) in the materials. Both the packaging and the food product can be part of this cycle. In some cases, the inedible parts of food products may serve as resources for new packaging materials (e.g., orange peels, nut shells). Furthermore, used cooking oil can be collected and converted into animal feed or biofuel. The most encompassing strategy in Figure 12 is to rethink the whole system and reconsider all elements and processes in the system. The different strategies are discussed in more detail below.

7.1 | Resource

The "Resource" strategy implies changing the source of the (raw) material for the packages. To reduce the impact on the environment, designers can try to use materials that have a lower impact. Materials can be fossil based, such as plastics; they can be plant based, such as paper or biobased plastics; or they can be mineral based, such as metal or glass.

The term "bioplastic" can refer to polymers that are biobased, biodegradable, or both, which can be confusing (Figure 13). The term "biobased" or "biosourced" implies that the monomers come from renewable, mostly vegetable, sources. Polymers that are synthesized from bio-derived monomers, such as bio-PET and bio-PE, are chemically identical to their fossil-based

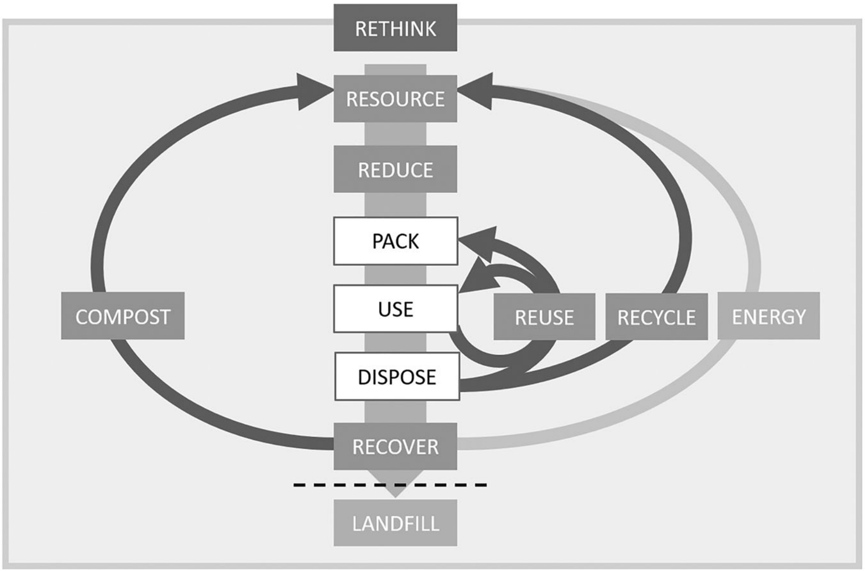

FIGURE 12 Circular packaging system diagram illustrating the continuous flow of materials in a circular packaging economy (adapted from Ellen MacArthur Foundation, 2013).

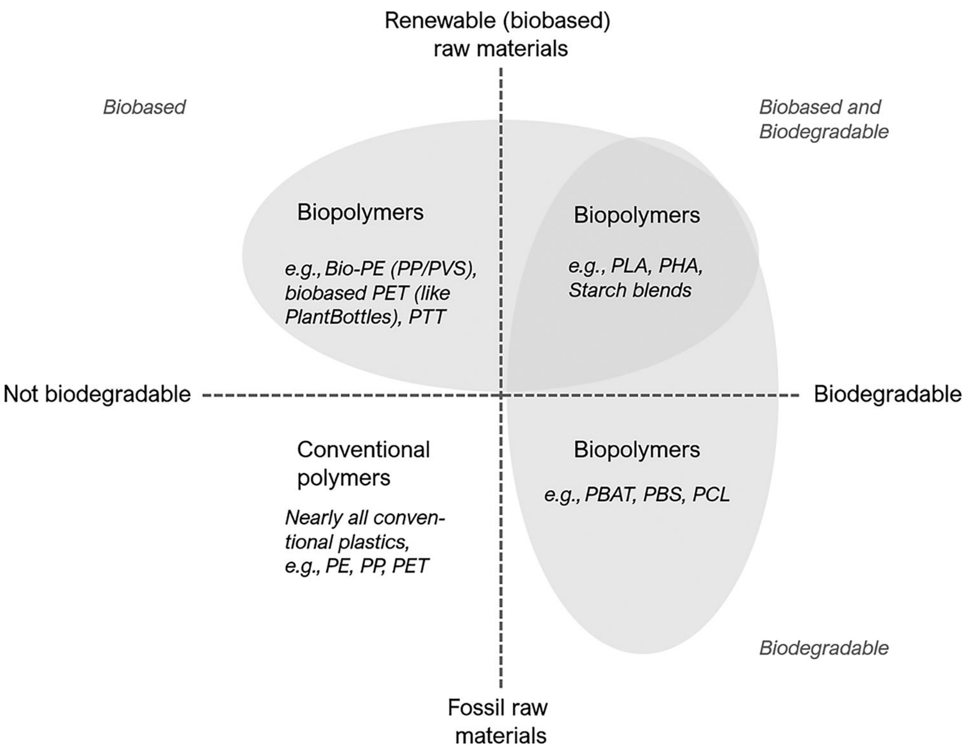

FIGURE 13 Overview of different types of bioplastics (adapted from Endres & Siebert-Raths, 2009). PBAT, polybutylene adipate terephthalate; PBS, polybutylene succinate; PCL, polycaprolactone; PE, polyethylene; PET, polyethylene terephthalate; PHA, polyhydroxyalkanoates; PLA, polylactic acid; PP, polypropylene; PVA, polyvinyl alcohol; PVS, polyvinyl siloxane; PTT, polytrimethylene terephthalate.

counterparts and thus have the same advantages (e.g., good barrier properties) as well as the same disadvantages (e.g., not biodegradable) (Molina-Besch & Olsson, 2022). Whether a material is biodegradable or not depends on the chemical structure of the material, independent of the resource used to make it. Particularly the presence of ester linkages in certain polyesters increases degradability, while polymers like PE and polypropylene (PP) lack these linkages and resist bacterial or fungal degradation. Environmental factors like temperature, oxygen, and microorganisms influence the rate and extent of biodegradation (see Section 7.5) (Molenveld et al., 2020).

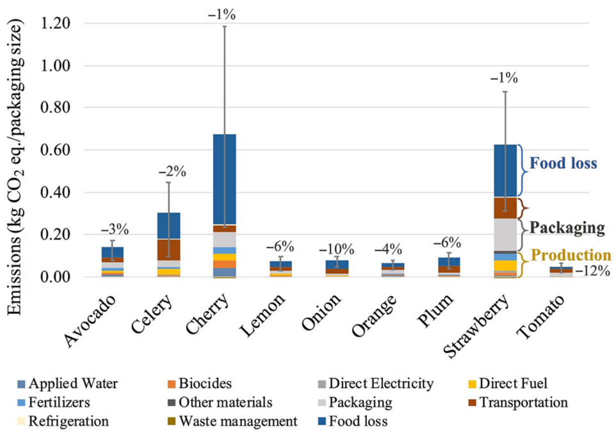

FIGURE 14 Greenhouse gas emissions for nine fruits and vegetables at the consumer level in typical retail packaging and sizes. The percentages above the bars indicate the changes in greenhouse gas emissions when switching from typical packaging to alternative packaging. Typical packaging is polyethylene (PE) bags for avocados, celery, lemons, onions, oranges, plums, and tomatoes; PE pouches for cherries; and PET clamshells for strawberries. The alternative packaging includes polylactic acid bags for cherries and strawberries, and no packaging for avocados, celery, lemons, onions, oranges, plums, and tomatoes (reprinted with permission from Qin & Horvath, 2022).

Figure 14 illustrates the impact of food production, packaging, and transportation on greenhouse gas emissions for various fruits, emphasizing the significance of informed decisions in packaging choices for environmental benefits. Biodegradable plastics may reduce greenhouse gas emissions by 10% for onions, but their limited barrier properties offer only a 1% reduction for perishable fruits like cherries and strawberries. While they can lower emissions, the trade-off in preserving freshness and preventing food waste requires careful consideration when choosing packaging (Qin & Horvath, 2022). Although polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) have been the focus of many sustainable packaging studies due to their biodegradability and mechanical performance (Yeo et al., 2024), further studies are needed to improve the barrier properties, mechanical characteristics, and biodegradation mechanisms of biopolymers in complex environments (Arif et al., 2022). Continued advancements in nanocomposite and additive manufacturing technologies will undoubtedly pave the way for next-generation packaging solutions that are both environmentally friendly and effective in preserving food quality.

Biopolymers from renewable biological sources are promising eco-friendly materials for food packaging as they exhibit properties such as bioactivity, renewability, biocompatibility, biodegradability, and hydrophilicity, making them ideal for sustainable food packaging applications (Khalid & Arif, 2022). Polysaccharide-based biomaterials, such as cellulose, chitosan, alginate, and starch, are widely used in food packaging. Cellulose derived from plants and microorganisms is the most used polysaccharide, while animal-based proteins like whey and gelatine provide barrier properties for packaging. Gluten protein from wheat and zein from corn provide an eco-friendlier alternative to animal-based proteins, while keratin derived from feathers and hair offers a biodegradable alternative to petroleum-based materials (Das et al., 2024). Chitosan is a biopolymer with excellent oxygen barrier properties. Chitosan films, especially in combination with other biomaterials like cellulose, can enhance barrier properties and extend food shelf life by reducing oxygen permeability. Unfortunately, challenges remain in scaling up production and achieving cost-effectiveness for biobased packaging. High production costs, limited availability of raw materials, and the need for specialized processing equipment pose economic challenges for these sustainable alternatives (Das et al., 2024).

Among biobased and biodegradable polymers, starch, chitosan, and alginate are frequently used to develop edible coatings that enhance food quality and prolong freshness. These coatings are often used on packaging for products where direct food contact is essential, such as fruits and vegetables. In some cases, these films are further modified with nanoparticles (Chandran et al., 2024) and essential oils (Tabass et al., 2024) to improve their mechanical strength, barrier properties, and antimicrobial effects (Khalid & Arif, 2022). Moreover, a new study highlights the potential of edible active packaging made from cascara extract, a coffee byproduct rich in polyphenols and polysaccharides, to extend product shelf life, protect against contamination, and prevent oxidation without contributing to additional packaging waste. The cascara coating forms a brown film, which may be suitable for darker food products. However, designers must be careful when applying this packaging, as the coating can alter the taste, appearance, and smell of the product (Turan et al., 2024).

Nonedible biodegradable films are developed using polyvinyl alcohol, often modified with nanoparticles such as zinc oxide, magnesium oxide, titanium dioxide, graphene, silver, or carbon dots. These nanobiocomposite materials significantly extend shelf life and provide antimicrobial protection, especially against pathogenic bacteria such as *Escherichia coli* and *Staphylococcus aureus*. In addition to their excellent mechanical and barrier properties, these biocomposites offer antioxidant properties, thereby improving food safety (Khalid & Arif, 2022). These nonedible films are commonly applied to packaging for processed foods, meat products, and ready-to-eat meals, where the focus is on extending shelf life, ensuring product

FIGURE 15 "From Peel to Peel" is made from a culture of bacteria combined with fruit and vegetable leftovers; using different fruits creates sustainable packaging in a variety of colors (image credits: Emma Sicher).

safety, and maintaining quality during transportation and storage.

In terms of smart and sustainable food packaging, nanocellulose-based materials have attracted interest, particularly due to their shape memory and self-healing capabilities (Khalid et al., 2024). Nanocellulose derivatives such as cellulose nanocrystals and cellulose nanofibers have shown potential for the development of multifunctional materials that can respond to environmental stimuli, making them suitable for active smart biopackaging solutions (Khalid & Arif, 2022). Their inherent biodegradability, renewability, and mechanical properties make them promising candidates for future packaging innovations. Analogously, stimuli-responsive hydrogels enable the creation of dynamic and responsive packaging that can adapt to changing environmental conditions, such as temperature, humidity, or light (Arif et al., 2024). This ability allows food to stay fresh for longer, thereby reducing food waste and extending shelf life.

7.1.1 | Using waste streams

It seems promising to use byproducts and unavoidable food waste as raw materials for biobased food packaging that can be biodegraded into fertilizers for agriculture after use. Fruit and vegetable pulp is interesting in this respect because it can provide natural extracts and colorants with strong antioxidant or antimicrobial effects for application in renewable and biodegradable food packaging (Jung, 2019). Figure 15 shows a number of disposable packaging created by Italian designer Emma Sicher, who fermented food waste with bacteria and yeasts (Cohen et al., 2020). Other customizable materials include rice husks, banana peels, sugarcane bagasse, and marine biowaste. Natural fibers from palm residues improve polymer composites, while fish bone waste enables eco-friendly filament development by incorporating anchovy bone powder (10% and 20%) into PLA (Yoha & Moses, 2023). Nanotechnology can enhance food packaging derived from microorganisms and food byproducts with carbon dots, improving mechanical strength, barrier properties, and antimicrobial effects for sustainable packaging solutions (Moradi et al., 2023).

7.1.2 | Mycelium-based food packaging materials

Agricultural waste can be converted into composite materials using fungal mycelium, providing a sustainable alternative to secondary foam packaging. This mycelium-based foam is biodegradable and shows potential as a replacement for polystyrene (Tajuddin et al., 2023). Its stability, low toxicity, porosity, and biodegradability make it an environmentally friendly choice. Additionally, mycelium biocomposite samples demonstrate superior properties compared to expanded polystyrene. Although it absorbs more water, its degradability and sufficient shelf life make it suitable for packaging applications (Sivaprasad et al., 2021). The strength and biodegradability of the

FIGURE 16 Example of a molded pulp tray from 100% recycled cardboard.

material outweigh the limitation of moisture absorption, especially for dry items. Joshi et al. (2020) showcase successful growth of *Pleurotus ostreatus* mycelium on sugarcane bagasse, forming highly stable and thermally robust biodegradable bioblocks. These blocks possess five to six times greater mechanical strength than standard expanded polystyrene packaging. The study recommends further exploration of different substrates and fungus species, as well as consideration of pesticide residues and ash content in agro-industrial substrates (Aranda-Calipuy et al., 2023). These findings advance the development of sustainable mycelium-based food packaging materials, emphasizing the ongoing need for research in this domain.

7.1.3 | Molded pulp

Molded pulp, also named molded fiber, is a packaging material that is typically made from recycled paperboard and/or newspaper (Figure 16). It is used for protective packaging or for trays (such as egg cartons) and beverage carriers. For many applications, molded pulp is less expensive than expanded polystyrene, vacuum-formed PET, corrugated board, and foam because it is produced from recycled materials and can be recycled again after its life cycle (Debnath et al., 2022).

7.2 | Reduce

"Reduce" is a strategy that focuses on the dimensions of food packaging, like reducing wall thickness, reducing headspace, or using more efficient proportions. Reduce can also involve reducing the amount of material types in one packaging to facilitate circularity. Furthermore, economical bulk packs require less packaging material per unit of product. However, large portion sizes can lead to more food waste and thus more total discards in small families.

Figure 17 shows the challenge of determining optimal packaging material amounts. Sustainable product–packaging combinations depend on the right balance between product and packaging properties. Minimal packaging (underpacking) may lead to product damage and food waste, while excessive material (overpacking) contributes to unnecessary packaging waste. A life cycle assessment of cucumbers transported from Spain to Switzerland demonstrated the crucial role of packaging in minimizing overall environmental impact. Plastic wrapping significantly reduced food waste, despite its environmental cost. Awareness of this balance is essential for stakeholders and designers (Shrivastava et al., 2022).

7.3 | Recycle

The packaging industry uses 40.5% of all plastics produced in the European Union. However, the recycling rate remains low (34.6%), and more than 23% of plastic waste is still landfilled (Zhu et al., 2022). When designing for recycling, it is important to realize that recyclability depends not only on the material itself but also on the packaging structure. Recycling is challenging when different polymers coexist in food packages (Lai & Wong, 2022). By 2030, all plastic packaging in Europe must be recyclable under the circular economy strategy. Recycled plastics for direct food contact, like PET and high-density polyethylene (HDPE), must adhere to strict safety

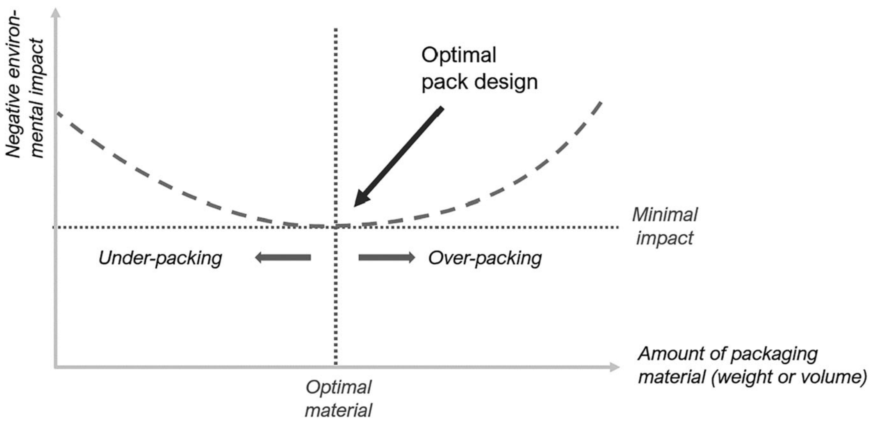

FIGURE 17 Impact of underpacking versus overpacking food products (adapted from Consumer Goods Forum, 2009).

standards set by the European Food Safety Authority (EFSA), with migration limits of 0.1 µg/L for PET and 0.06 µg/L for HDPE. These limits are due to concerns about substances that migrate from the plastic into the food, whether these substances were added intentionally or not. Polyolefins and polystyrene have shown challenges, as they are more susceptible to the passage of nonintentionally added substances, posing food safety risks. Currently, only recycled PET meets the required safety standards, highlighting the need for improved collection and cleaning processes and advanced analytical methods to ensure food safety in recycled packaging (Rung et al., 2023).

Life cycle analyses can help understand the impact of different material choices, considering multiple facets of the environmental impact, including the recyclability of the material, weight and transport, energy consumption in the production and recycling process, and so on (Humbert et al., 2009). A web-based decision support tool has been developed to select packaging material alternatives based on environmental impacts throughout the lifecycle, as depicted in Table 3. This tool enables designers to assess the disparities between existing packaging materials and the suggested alternatives, enabling environmentally sound decision-making (Gutta & Kuriger, 2013).

In terms of circular design, the biggest challenge for the metal and glass packaging industry lies in reducing energy consumption and switching to renewable energy sources while increasing the share of recycled materials. For paper and cardboard packaging, there is a need to replace the existing fossil-based polymer films and aluminum foil layers that are used for barrier properties and sealability but are problematic from a recycling perspective.

Materials, structure, shape, size, labeling, and components all influence recyclability. Several brands are showing a shift toward paper packaging, as they consider it a more sustainable and easily recyclable alternative. For instance, Absolut vodka is exploring the potential of a lighter, paper bottle and evaluating its transportation impact in the distribution channel (Packaging Europe, 2023). However, the paper bottle still needs a plastic liner to be suitable for beverages, which makes recycling difficult. A better example is the 100% paper tub that the Flora Food Group has developed for Flora plant butters and spreads. This package is made of compressed wet paper fibers, making it both waterproof and oil resistant (Qureshi, 2024). With this innovation, the Flora Food Group has found a way to move away from plastic and create a completely plastic-free solution (Figure 18).

FIGURE 18 A 100% paper-based packaging developed for Flora plant-based butter (image credit: Flora Food Group).

Adhesives, labels, and pigmentation also play an important role in the recycling process, as aggressive glues and additives can accumulate in recycled streams. In addition, colored recycled plastics have lower value and face challenges in being repurposed due to specific color-matching requirements. Therefore, introducing self-peeling labels, preventing ink bleeding, and adopting distinct packaging colors for food and nonfood items can have a significant impact on recycling efficiency (Kosior, 2023).

Designers must navigate a complex landscape of regulatory requirements governing food packaging, ensuring compliance with standards related to food contact materials, labeling, and environmental impact. The most

TABLE 3 Output of a web-based decision support tool for selecting packaging materials (Gutta & Kuriger, 2013).

Level of packaging	Material	Weight per unit	Climate change	Air quality	Ozone depletion	Waste	Energy
Primary	Aluminum	0.001	465.6	0.147	2.421	48	7440
Secondary	Corrugated board	0.025	101	0.001	53	20.7	2129
Tertiary	Hardwood	1	87.4	0.7	0.114	0.029	100
Total			654 kg CO_2 eq.	0.847 kg CO_2 eq.	55.535 kg CO_2 eq.	68.729 kg	9669 MJ

common of these regulations refers to Good Manufacturing Practice, governed by regulation No. 2023/2006 (European Commission, 2006). Plastics are subject to specific regulations, including No. 10/2011 (European Commission, 2011) and No. 282/2008 (European Commission, 2008), which set recycling targets. Despite being renewable, biobased plastics need to adhere to plastic regulations, in line with the Single Use Plastics Directive, promoting sustainable alternatives (European Commission, 2019). One such directive, EU Directive 2018/852, is geared toward achieving recycling quotas of 70% for all packaging materials and 55% for plastics (European Union, 2018). Furthermore, the revision of the Packaging and Packaging Waste Regulation aims for recycled content quotas of 30% for PET contact-sensitive packaging and 10% for other contact-sensitive packaging (European Commission, 2022). Meeting these legal requirements poses severe challenges. Collaboration with regulatory experts and adherence to best practices are integral to developing packaging solutions that meet legal obligations while prioritizing consumer safety.

The amount of packaging recycled also depends on the (local) recycling infrastructure and the demand for recycled materials. For glass, paper, and increasingly PET, recycling streams are well organized in Western Europe and beyond. Deposit systems for empty packaging such as PET bottles or aluminum cans can incentivize consumers to return packaging for recycling. The EU Circular Economy Action Plan (European Commission, 2020) sets a target that by 2030 all plastic packaging should be reusable or recyclable at reasonable costs. This requires the creation of a closed loop for the recycling of food packaging materials. Efficient waste collection is a crucial initial step in the circular economy. Digital tools such as infrared sensors and geographic information systems can help with waste collection, inventorying surface types (e.g., vegetation, water, urban areas, waste accumulations), and optimizing waste transport.

7.4 | Reuse

In most cases, reusable packaging is the most environmentally friendly packaging solution (Megale Coelho, Corona, & Worrell, 2020). Material-optimized refillable solutions (Lofthouse et al., 2017) and global reuse platforms (the Loop) have already been introduced to the market (Figure 19). However, there are some cases where single use is preferable. In particular, transportation distances, the number of reuse cycles, and the weight and volume of the packages determine the transportation fuel consumption and space requirements. Comparative studies have shown that reusable options like polypropylene

FIGURE 19 The Carrefour Group and Loop offer consumers a "zero waste" experience utilizing reusable and returnable packaging (image credit: Loop).

(PP) and glass cups outperform single-use PLA cups after approximately 10 uses (Almeida et al., 2018). Research has also explored the potential of enhanced PLA films with nanostructured composites for improved properties and reusability (Peter et al., 2021). While handling fresh produce in reusable plastic crates can improve sustainability in the supply chain, it also poses challenges in terms of microbial safety. A study on fresh cauliflowers showed that *Salmonella* cross-contamination risks were higher via PP from reusable plastic crates compared to corrugated cardboard or medium-density fibreboard (MDF) from wooden boxes, despite a lower environmental impact with a lifespan of only 15 rotations compared to single-use alternatives (López-Gálvez et al., 2021). Hence, setting up efficient take-back and cleaning processes for reusable packaging remains a major challenge.

Loop, a circular e-commerce packaging system launched in 2019, offers multiuse packaging for products from major brands such as Unilever and Nestlé via subscription-based e-commerce. The ownership of Loop packaging remains with the producers, and with each delivery the packaging from the last delivery is collected for cleaning and refilling. While e-commerce in the food market has increased packaging material usage, reusable e-grocery packaging solutions are still limited. Liviri Fresh has developed insulated reusable boxes for home delivery of refrigerated food in the United States (Megale Coelho, Corona, ten Klooster & Worrell, 2020). Deposit systems can help stimulate consumers to return packaging for refilling or recycling.

Since July 3, 2021, several single-use plastic products are no longer allowed to be placed on the EU market. Examples include plates, cutlery, food and beverage containers, stirrers, and straws made of plastic or bioplastic. Since January 1, 2024, there has been a complete ban on the use of disposable plastic cups and food packaging on site (Netherlands Enterprise Agency, 2024).

7.5 | Recover

Figure 12 shows that there are two ways in which resources from packaging materials may be recovered, either by composting or by recovering the energy through incineration. If materials can be broken down by microorganisms into carbon dioxide (CO_2), water, and/or methane, they are called biodegradable or biodecomposable (Molenveld et al., 2020). Biodegradation is highly dependent on the conditions in the air, water, and soil. For instance, PLA, polybutylene succinate (PBS), and PHAs have been put forward as suitable alternatives for food packaging applications. However, producing bioplastics with optimal barrier properties at competitive costs and without compromising the biodegradability of the material remains a challenge. Biodegradability is particularly important when recovery of plastics is difficult or when plastics end up in the environment (Molina-Besch & Olsson, 2022).

PLA is suitable for composting in industrial facilities but not for home composting, as it requires temperatures around 60°C. Decomposition depends on product geometry and thickness, while the presence of additives and heavy metals poses ecotoxicity risks. PLA can be transformed into methane through fermentation or chemical recycling by hydrolysis, transforming it into lactic acid for renewed production. Mechanical recycling is also an option. PBS is both biodegradable and industrially compostable per EN13432 standards (Molenveld et al., 2020). PHAs are compostable at home and biodegradable in anaerobic fermentation plants, soil, and marine environments (Molenveld et al., 2022).

In most European countries, packaging that cannot be reused or recycled is incinerated. When materials are burned, energy is released from the material, which can be used for generating heat or electricity. Incineration is better than landfill, in which the packaging material is regarded only as waste, and nothing is recovered. However, incineration is the least preferred option, as it is relatively inefficient and generates waste products like ashes and exhaust that contain toxic compounds and greenhouse gasses. Typical efficiencies of electricity generation compare poorly with coal- or gas-fired power plants, while greenhouse gas emissions per unit of electricity almost double those of natural gas generation. The situation is slightly better for heat generation, but performance is no better than that of domestic gas-fired boilers. The situation is worse when emissions of non-fossil CO_2 from waste incineration are considered, as emissions effectively double (Hogg, 2023). How to deal with waste products from incineration may be regulated in Western countries, but not in many other parts of the world and may, therefore, cause additional environmental pollution.

7.6 | Rethink

Designers are exploring innovative concepts like package-free shopping and reusable packaging systems to foster a more sustainable food packaging ecosystem. Here, the "Rethink" strategy refers to re-evaluating and reimagining the entire process of packaging design, production, and usage to minimize environmental impact. This involves questioning traditional practices and exploring innovative solutions to create packaging that is eco-friendlier and more sustainable. The rethink strategy is concerned with redesigning the full food packaging system, including the chain from raw packaging materials and the interaction with the food product to logistic requirements, consumer behavior, and the business model. It may also imply changing some of the rules and regulations connected to the system. It is considered to be the most effective option to reduce environmental impact. This strategy is probably the one where designers can contribute the most, as they are trained to think outside the box. Rather than focusing on a specific usage problem or material limitation, this strategy calls for new visions on the use and function of packaging.

7.6.1 | Package-free stores

For most food products, packaging-free storage, transport, and distribution are nearly impossible for practical reasons, especially for foods that are consumed thousands of miles away from where they were grown and processed. Packaging has an important protective function, similar to the skin of a fruit. Eliminating food packages would have profound consequences for the way retail models are currently organized and managed. For example, Dutch retailer Pieter Pot provides an online food store that uses glass preserving jars for all products. Customers pay a deposit per jar and return the jars when they are empty, and the store cleans the jars for reuse. Hence, the store developed a system of reusable packages to compensate for the absence of retail packages (Beitzen-Heineke et al., 2017).

7.6.2 | Edible packages

Edible packaging formulations based on biopolymers and active compounds extracted from biowaste offer great opportunities to decrease the devastating overuse of plastic-based packaging (Kumar et al., 2022). Some start-ups have transformed these concepts into actual products. For example, Do Eat (Belgium) (https://www.ecolotec.com/do-eat) offered edible packaging materials based on potato starch and water, such as sandwich rings, cupcake holders, and food bags (Hamed et al., 2022). Skipping Rocks Lab (UK) (https://www.notpla.com/) developed an edible material named Notpla from seaweed and created the Ooho bubbles that can contain water, beverages, or sauces. Besides the possibility of eating the material along with the product, the package can degrade in nature within 4–6 weeks (Figure 20).

In some cases, regular food ingredients have been used to make edible packages or containers, such as the traditional waffles or cones that are used to consume ice cream. More recently, the Scoff-ee Cup was designed for the fast-food chain KFC in the shape of a cardboard coffee cup.

FIGURE 20 An example of edible and eco-friendly packaging: Notpla Ooho bubbles made from seaweed (image credits: Adam Flanagan).

It had a double layer of white chocolate coating around a biscuit wrapped in sugar paper designed to withstand the heat of espresso coffee. In addition, KFC in Hong Kong introduced a new edible wrapper made of rice paper designed by Ogilvy & Mather Group HK (Hamed et al., 2022).

7.6.3 | Dissolvable packaging

A group of students from Aalto University in Finland developed a dip in a biobased liquid that gives cucumbers a protective film that can simply be washed off, offering a renewable and biodegradable alternative to plastic wraps. It is called the DipWrap. The dip mixture contains a jelly-like, red algae-based substance from agar agar, carnauba wax, and cellulose nanocrystals. The team believes that the dipping treatment could also be used for other vegetables and fruits (Kallai et al., 2021). However, having such a wrap would also require different behavior from consumers, as they need to wash it off before eating the product.

8 | DISCUSSION

In this paper, we have provided an overview of the various challenges designers face when developing new food packaging, including aspects of food preservation and safety, manufacturing processes, distribution and storage, marketing, consumer usability, and disposal. While many technological innovations (e.g., active and smart packaging, sealing options, degradable and recyclable materials, 3D printing possibilities) are being proposed, these will only be meaningful if they are part of an integrated design solution that meets the needs of food producers, distributors, retailers, and consumers together. In addition, solutions should contribute to society at large, for instance, by reducing the impact on the environment, limiting the amount of food that is being wasted, and simultaneously considering the impact that packaging waste can have. Therefore, designers face the task of innovating within the constraints of many stakeholders, looking for optimal solutions in a complex system. Some of the challenges that we identified within the current system include avoiding food waste, for instance, by optimizing packaging size and improving its resealability. Another challenge is to make the packaging designs more inclusive by addressing product usability for an increasingly aging population. The choice of materials, packaging dimensions, text and graphics, and the ways to perform different functions (e.g., open and close, hold, pour, shake, heat) all provide designers with opportunities for packaging improvements. Alternatively, designers may come up with solutions that challenge the current system and can engage a large group of, possibly different, stakeholders. This requires thinking about what partnerships are needed to innovate such radical packaging solutions designed for a sustainable society.

In their endeavors, designers need to consider the freedom (or lack thereof) to provide new solutions in an area that is highly regulated, in order to ensure that people have access to safe and nutritious food products. For instance, EU regulations specify essential requirements addressing product safety, sustainability, and inclusivity (European Commission, 2006, 2009, 2011, 2022; European Parliament, 2004). These packaging regulations dictate, for example, general requirements for materials in contact with food, with particular attention to active and smart materials. Packaging materials can contain intentionally added substances, such as antioxidants, antimicrobials, and nanoparticles, that serve to enhance packaging and food quality and safety. However, they can also contain nonintentionally added substances, such as impurities, contaminants from recycled materials, polymer degradation products, and reaction products between polymer components or with food. The European Food Safety Authority (EFSA) recommends toxicological thresholds for these substances as they may compromise food safety and organoleptic properties. With regard to sustainability, all packaging must meet specific criteria related to manufacturing, composition, and reusability or recoverability. By the end of 2024, EU countries are expected to establish producer responsibility schemes for all packaging. Notably, plastics, including biobased plastics, are subject to specific recycling goals, and all single-use plastics are banned. Other EU Directives urge designers to incorporate sustainable alternatives. Furthermore, the International Standardization Organization (ISO) provides accessibility guidelines, addressing easy opening, opening force, tool necessity, and intuitiveness of the mechanism to assure inclusivity for users with varying abilities.

Besides the input from scientific inventions and government regulations, we see a clear role for public and private initiatives in supporting designers when making choices for specific materials and applications. In our overview, we made extensive use of the insights and models developed by the Ellen MacArthur Foundation, the Consumer Goods Forum, Packforward, the Dutch Packaging Centre (NVC), Milieu Centraal, the Netherlands Institute for Sustainable Packaging (KIDV), and the Institute for Bioplastics and Biocomposites (IfBB). Besides providing the necessary background information, these initiatives try to translate scientific knowledge into practical applicability and, thereby, function as a bridge between science, government, and design practice. Consequently, they not only function as sources of information but also provide practical advice and tools that help designers implement traditional and novel applications in their designs.

9 | CONCLUSION

We hope that the overview we have outlined, including the tables with more detailed information, provides future food packaging designers with the essential background knowledge to enable them to contribute to innovations in this challenging area. As the challenges in food packaging design are multifaceted and involve multiple stakeholders, they require designers to have an open mind for all considerations and integrate information from multiple disciplines. In particular, the challenge of devising sustainable solutions that reduce both food waste and packaging waste requires the utmost creative power, especially as governments start to take drastic measures to discourage certain practices and ban solutions that they see as causing too much pollution (e.g., single-use plastics). This requires exploring renewable resources, further investigating and deepening the principles of reduce, recycle, reuse, recover, and rethink, with a strong focus on enhancing circularity, while also developing and testing new approaches.

Given that people eat every day, and that food production is a huge global industry with a big turnover that is of direct relevance to many aspects of human life, like personal health, social interactions, and nature preservation, this is a domain where designers can have a major impact on multiple levels. Hence, we hope to encourage designers to actively engage with this topic and contribute to an area that is in need of innovative ideas to optimize the health of people and the planet they live on.

AUTHOR CONTRIBUTIONS

Deniz Turan: Writing—original draft; writing—review and editing; visualization. **Barbera M. Keukens**: Writing—original draft; writing—review and editing; visualization. **Hendrik N. J. Schifferstein**: Writing—original draft; writing—review and editing; conceptualization.

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ChatGPT 4.0 was used to generate a comprehensive table with structured information about packaging materials (Appendix). The information in the table was subsequently reviewed and amended where needed by the authors to ensure the quality of its content.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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APPENDIX
OVERVIEW OF PACKAGING MATERIALS AND THEIR MAIN CHARACTERISTICS

Group	Material	Food product	Product characteristics/food compatibility	Consumer/marketing aspects	Environmental issues	Conversion at factory
Polyolefins	Low-density polyethylene (LDPE)	Fruits and vegetables; milk; cheese; bakery products; chocolate	Good water vapor barrier; good liquid-tight sealing; good resistance to acid, alkali, and inorganic solutions; poor gas barrier; temperature resistance (−40 to 90°C)	Flexible; smooth; slight haze or translucency; good printability; lightweight; versatile	Recycling challenges; pollution concerns; exploration needed	Cast film extrusion; blow molding
	Linear low-density polyethylene (LLDPE)	Fruits and vegetables	Better chemical resistance than LDPE; good performance at low and high temperature; good strength and puncture resistance; good heat sealing	Flexible; impact-resistant; good printability; versatile	Recycling challenges; pollution concerns; exploration needed	Film extrusion (with metallocene catalysts); extrusion blow molded bottles
	Very low-density polyethylene (VLDPE)	Fresh produce; milk; cheese; meat; vegetable oils; yoghurt; breakfast cereals	Excellent stretchability; tear and impact strength; optical properties and sealing (low-temperature hot tack property); chemical resistant	Flexible; soft; pliable	Recycling challenges; pollution concerns; exploration needed	Blended with other polyethylene (PE) and polypropylene (PP) resins; cast film extrusion; multilayer co-extruded film

(Continues)

Group	Material	Food product	Product characteristics/food compatibility	Consumer/ marketing aspects	Environmental issues	Conversion at factory
	High density polyethylene (HDPE)	Milk and dairy products; condiments and sauces; edible oils; frozen food; snacks; cereal and grain products; fruits and vegetables	Good resistance to oils; excellent moisture protection; better gas barrier than LDPE	Strong; rigid; good printability	Recyclable; suitable for reuse; lower environmental impact; easily recycled in semi-rigid form but identification and separation more difficult for films	Extrusion blow molded into bottles
	Polypropylene (PP)	Snacks; fresh produce; dairy products; frozen food and ice cream; condiments; bakery products; instant pot noodles; candy and confectionery	High water vapor barrier; medium gas permeability; good resistance to greases and chemicals; heat-resistant; film-hinges	Versatile; good gloss; high clarity	Recyclable, with challenges; lightweight	Blow and injection molding (rigid); film extrusion (flexibles)
Copolymers of ethylene	Ethylene-vinyl acetate (EVA)	Fresh meat; breakfast cereals	Good flexibility and toughness at low temperature; excellent adhesion to metals, e.g., aluminum	Flexible; soft; suitable for softer packaging	Renewable source; end-of-life disposal challenges	Extrusion coating of PET and bioriented PP films; stretch film and cling-wrap purpose
	Ethylene vinyl alcohol (EVOH)	Milk powder; wine in bag-in-box packs; ketchup; mayonnaise; fruit juices; carbonated beverages; beer	Superior barriers against gasses, odors, aromas, solvents; high mechanical strength and elasticity	Excellent barrier properties; extends shelf life	Recycling challenges; end-of-life concerns	Co-extrusion of films with PE and EVA and blow molding into bottles with PP, PET, and HDPE; rigid and semirigid containers and paperboard beverage cartons
	Ethylene acrylic acid (EAA)	Meat; cheese; snack food	Good water vapor barrier; superior strength; toughness; excellent adhesion to metals (e.g., aluminum) and hot tack; used in coatings	Adhesion; clarity	Renewable source; environmental footprint depends on use	In skin and blister packaging; adhesive lamination as an extrusion coating tie layer

(Continues)

Group	Material	Food product	Product characteristics/food compatibility	Consumer/ marketing aspects	Environmental issues	Conversion at factory
	Ionomers	Meat; cheese	Good heat sealing; excellent hot tack; good impact and puncture resistance	Toughness; transparency; impact resistance	Recycling challenges; environmental impact depends on use	Seal layer in extrusion-coated aluminum foil; laminated or coextruded films with polyesters
	Cyclic olefin copolymer (COC)	Fresh cut produce bags; pouches for drinks; cereals; candies; soups	Excellent moisture barrier; better barrier against aromas and hot tack than LDPE; high heat resistance	Clarity	Recyclable; lower environmental impact	Used in polyolefin blends
Substituted olefins	Polystyrene (PS)	Frozen food; coffee; ice cream; honeys and syrup; fresh produce; meat and produce trays; egg trays; disposable dinnerware; yoghurt cups; portion pack cups	Excellent optical properties; good tensile strength; water barrier (extensible PS sheet)	Lightweight; insulation properties; excellent printability	Recycling challenges; exploration needed	Tandem extrusion for PS foam sheet; thermo-formed into small cups
Polyesters	Poly(ethylene tereph-thalate) (PET)	Carbonated beverages; oven bags; vegetable oils; milk; cheese; bakery products	Excellent transparency; chemical resistance; temperature stability; great tensile strength	Transparent; lightweight; easily recyclable; good printability	High recycling rate; Production of recycled PET (rPET); deposit system for PET bottles	Film extrusion; injection molded pre-forms; stretch blow molded bottles
	Poly(ethylene naphtha-late)	Hot fill food (e.g., baby food; ketchup); beer	High gas barrier; excellent tensile strength; heat stability	High-temperature resistance; suitable for hot-fill	Limited recycling; exploration needed	Reuseable; high cost
Polycarbonate		Due to concerns about BPA, many manufacturers have transitioned to using BPA-free plastics or alternative materials				

(Continues)

Group	Material	Food product	Product characteristics/food compatibility	Consumer/ marketing aspects	Environmental issues	Conversion at factory
Polyamides	Nylon	Vacuum packaging of cheese; bacon; fresh and processed meats; frozen foods	Excellent thermoformability; high temperature resistance; mechanical strength; flex-crack resistance	Strong; barrier properties; clarity; good printability	Recycling challenges; exploration needed	Coextruded films or laminates with other materials
Metals	Tinplate (cans)	Beer cans; carbonated beverages; fruit and vegetables; vegetable oils; milk powders; coffee	Superior mechanical strength; impermeable; strong and formable; light and gas barrier; good thermal conductivity; resistance to high temperature; resistant to corrosion; withstands heat processing	Easy to decorate; might require a can opener; shape limitations	Recyclable; magnetic thus easily separated; heavier than aluminum	Tinplate (tin-coated steel plate); metal cans
	Aluminum	Nespresso cups; carbonated beverage cans; layer in laminates for, e.g., soup pouches; tea; coffee; chocolate wrappers	Cannot be welded; limited structural strength; impermeable to moisture and gases; resistant to corrosion; withstands heat processing; easy to decorate; lightweight; good portability; lightweight; not breakable	Limited shapes; recyclable; lightweight; economic incentive to recycle	Separation difficulties in laminated form; relatively expensive but value encourages recycling	Aluminum cans; film layer in flexible packaging
Glass		Fruit and vegetables; sauces; condiments; wine; beer; baby food	Impermeable to moisture and gases; nonreactive (inert); withstands heat processing; can be colored for light-sensitive products; heavy; brittle and breakable; needs a separate closure	Transparent: allows consumer to see product; poor portability: heavy and breakable; relatively difficult to decorate; fresh and quality look and feel; high consumer trust; recycling habit in place	Reusable; recyclable; often contains recycled content; heavy and bulky to transport; production (and recycling) is energy intense; collection logistics well organized	Blow-and-blow (blow molding)

(Continues)

Group	Material	Food product	Product characteristics/food compatibility	Consumer/marketing aspects	Environmental issues	Conversion at factory
Paper	Cardboard packaging	Breakfast cereals; tea boxes; cookies; bouillon cubes boxes; meal kits	Low weight; plano transport; used as primary layer or secondary pack layer: cookies, bouillon cubes, etc.; poor barrier to moisture and gases	Eco-friendly look and feel; recycling habit in place	Renewable; recyclable; biodegradable; recycled extensively and at low cost; recycling logistics well organized; ink or (thin) plastic layers for moisture protection are hard to separate for recycling	Cutting, folding and gluing
	Paper laminates	Milk; yoghurt; butter; fruit juices (tetra pack)	Lamination of paper, polymer films and sometimes aluminum; great barrier properties; aseptic filling possible	Fresh and quality look and feel; high consumer trust; convenience; great printability	Renewable or recycled sources possible; hard to separate layers for recycling	Plastic layers (and aluminum layer) laminated onto paperboard sheets
	Paper pulp	Egg cartons	Limited strength; vulnerable to moisture	Natural and sustainable image	Renewable; biodegradable	Pulping and forming
	Corrugated cardboard	Pizza boxes; secondary packaging; outer cases in supermarket	Sturdy; lightweight; recyclable; bulky; not waterproof	Packaging strength	Renewable source; recyclable	Corrugation and box making