SİDAS MEDYA
Akademik Gıda®
ISSN Online: 2148-015X
https://dergipark.org.tr/tr/pub/akademik-gida

Akademik Gıda ***Özel Sayı: Yeşil Dönüşüm / Special Issue: Green Transformation*** (2024) SI65-SI77
DOI: 10.24323/akademik-gida.1554476

Review Paper / Derleme Makale

Trends in Sustainability and Innovative Food Packaging Materials: An Overview

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Received (Geliş Tarihi): 01.05.2024, Accepted (Kabul Tarihi): 23.08.2024
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ABSTRACT

Globally, 1.3 billion tons of food are wasted or lost every year. This loss is valued at US $2.6 trillion and accounts for 8-10% of greenhouse gas emissions (GHG). Food waste is a significant source of greenhouse gas emissions and results in a waste of natural resources. Therefore, reducing food waste can help diminish GHG emissions, improve food security, and promote healthy food systems. Packaging plays an important role in protecting food, enhancing quality and safety, and reducing food losses. Innovative and sustainable packaging strategies are necessary to decrease waste accumulation, particularly of plastics, safeguard food quality and safety, and reduce food losses and waste. Sustainable packaging aims to enhance the effectiveness of design and the use of environmentally friendly materials. This review provides an overview of the sustainable status of common packaging materials such as plastic, glass, metal, and paper/cardboard based on the circular economy, which includes recycling, reuse, composting, and bio-based packaging. The study examines new developments in food packaging materials in response to the growing demand for environmentally sustainable alternatives. Several applications from food companies and sustainable studies are discussed regarding continuous availability without impacting the environment. Ongoing research and technological advancements, such as material reduction, the development of innovative new materials like bio-plastics, and improvements in recycling, will contribute to increasing the acceptance of sustainable packaging. Definitions, requirements, limitations, legislation, and applications of sustainable packaging are explored. Sustainable packaging can stimulate economic growth and offer new opportunities for companies, notably by helping the environment and reducing the carbon footprint. However, the cost of sustainable packaging can still be challenging for small businesses. Determining whether consumers are willing to pay more for sustainable packaging is also crucial in this transition.

Keywords: Sustainability, Sustainable packaging, Eco-friendly materials, Biopolymer, Less-waste

Sürdürülebilirlik ve Yenilikçi Gıda Ambalajlama Malzemelerindeki Eğilimler: Genel Bakış

ÖZ

Dünya çapında her yıl 1.3 milyon ton gıda israf ediliyor veya kayboluyor. Bu, 2.6 trilyon ABD doları değerinde ve sera gazı emisyonlarının %8-10'unu oluşturuyor. Gıda israfı, sera gazı emisyonlarının ve doğal kaynakların israfının başlıca kaynaklarından biridir. Bu nedenle, gıda israfını azaltmak, sera gazı emisyonlarını azaltmaya, gıda güvenliğini artırmaya ve sağlıklı gıda sistemlerini teşvik etmeye yardımcı olabilir. Ambalaj, gıdayı korumada, kalite/güvenliği iyileştirmede ve gıda kayıplarını azaltmada önemli bir rol oynar. Atık birikimini, özellikle plastikleri azaltmak, gıda kalitesini/güvenliğini korumak ve gıda kayıplarını ve israfını azaltmak için yenilikçi ve sürdürülebilir ambalaj stratejileri gereklidir. Sürdürülebilir ambalaj, tasarımın etkinliğini ve çevre dostu malzemelerin kullanımını artırmayı amaçlamaktadır. Bu inceleme, geri dönüşüm, yeniden kullanım, kompostlama ve biyolojik bazlı ambalajı içeren dairesel ekonomiye dayalı olarak plastik, cam, metal ve kağıt/karton gibi yaygın ambalaj malzemelerinin sürdürülebilir durumuna genel bir bakış sunmaktadır. Çalışma, çevreye uygun ikamelere olan artan ihtiyaca yanıt olarak gıda ambalaj malzemelerinde yeni gelişmeleri incelemektedir. Gıda şirketlerinin çeşitli uygulamaları ve sürdürülebilir çalışmalar, çevreyi etkilemeden sürekli kullanılabilirlik konusunda tartışılmıştır. Malzeme azaltma, biyo-plastikler gibi yenilikçi yeni malzemeler ve geri dönüşümdeki iyileştirmeler gibi devam eden araştırmalar ve teknolojik gelişmeler, sürdürülebilir ambalajın kabulünü artırmaya katkıda bulunacaktır. Sürdürülebilir ambalajın tanımları, gereklilikleri, sınırlamaları, mevzuatları ve uygulamaları tartışılmaktadır. Sürdürülebilir ambalaj, ekonomik büyümeyi teşvik edebilir ve şirketlere yeni fırsatlar sunabilir, en azından çevreye yardımcı olarak ve karbon ayak izini azaltarak. Ancak, sürdürülebilir ambalajın maliyeti küçük işletmeler için hala bir zorluk olabilir. Tüketicilerin sürdürülebilir ambalaj için daha fazla ödeme yapmaya istekli olup olmadıklarını belirlemek de bu geçişte önemlidir.

Anahtar Kelimeler: Sürdürülebilirlik, Sürdürülebilir ambalaj, Çevre dostu malzemeler, Biyopolimer, Az atık

INTRODUCTION

Over 25% of the annual global food supply is lost or wasted. According to the Food and Agriculture Organization (FAO) and the United Nations Environment Program (UNEP), the annual global volume of wasted or lost food amounts to 1.3 billion tones, valued at US$2.6 trillion, and contributes to 8-10% of greenhouse gas (GHG) emissions. Food wastage serves as a significant contributor to greenhouse gas (GHG) emissions and the depletion of natural resources. Therefore, mitigating food waste can effectively reduce global GHG emissions, enhance food security, and foster sustainable food systems [1, 2].

In addition to serving as a means of product protection and preservation, extending shelf life, providing information, ensuring traceability, and enhancing the convenience of food products, packaging plays a key role in facilitating the monitoring of food safety and quality throughout the entire supply chain - from production to consumption and reuse/recycling. Appropriate packaging stands as a pivotal element in enhancing food preservation, quality, safety and in the minimizing of food waste at almost every stage of the food chain [3]. As per the U.S. Environmental Protection Agency (EPA), food and its corresponding packaging materials contribute to almost half of the total municipal solid waste generated. Commonly used food packaging materials include plastic, glass, metal, paper, corrugated fiberboard and laminates/extrusions of paper and plastics. Polymeric materials emerge as the predominant choice among packaging options for food, owing to their lightness, cost-effectiveness, formability, flexibility, durability and versatility in terms of color and transparency. In the prevailing plastic-centric economy, packaging materials mostly rely on petroleum-based polymer sources. Despite witnessing a twofold increase in global plastic production over the past two decades - escalating from 234 million tons in 2000 to 460 million tons in 2021 - only 9% of the plastic waste generated in 2021 underwent recycling processes [4].

The disposal of significant quantities of packaging waste into landfills following the single-use utilization of food packaging exacerbates environmental problems by contributing to issues such as leaching into aquatic ecosystems and the proliferation of microplastics. With their omnipresence microplastics, tiny particles less than 5 millimeters in size, have become a matter of growing concern for the environment and human health. Despite a temporary reduction in plastic consumption (2.2%) amid the COVID-19 pandemic, the surge in littering, the heightened reliance on takeaway packaging, and the increased single-use of medical plastic items like masks have resulted in a waste generation world [5, 6].

The environmental repercussions associated with packaging materials, whether during their manufacturing or post-consumption disposal, stand as a significant focal point of concern [7]. Frequently, these materials are discarded following a brief period of utility, thereby contributing to environmental concerns as described previously. In order to minimize the environmental footprint of a packaging, both the intrinsic and the extrinsic attributes of the packaging can be changed. In this respect, packaging sustainability is expressed as the endeavor to minimize the package's footprint through altering the package more environmentally friendly materials [8].

DIMENSIONS of SUSTAINABILITY

The fundamental dimensions of sustainability are economic, environmental and social considerations as user-friendliness [9, 10]. There is a growing attention on the environmental aspect while the economic and social considerations are often ignored. It is evident that the adoption of sustainable packaging practices, characterized by the utilization of eco-friendly materials and conscientious design approaches, is imperative to mitigate any adverse environmental impacts of packaging while preserving food quality and ensuring food safety [11]. Packaging plays an essential role in encouraging sustainable patterns of food consumption, seeking to curtail waste generation and mitigate environmental harm through the adoption of sustainable packaging solutions. Strategies aimed at minimizing waste within the context of sustainable packaging include: (a) Reduction and reusability principles; (b) Substitution of traditional materials with recyclable or compostable alternatives; and (c) Promotion of recycling practices to facilitate the creation of recyclable packaging materials derived from reusable sources, thus creating a sustainable approach characterized by reduced packaging waste and enhanced resource efficiency [12].

The dynamic and rapid evolution of consumption patterns has facilitated the expansion and heightened significance of the packaging sector. Consequently, packaging manufacturers are compelled to proactively engage in initiatives aimed at safeguarding the future and fostering sustainable production practices through the development of eco-conscious products that align with evolving consumer behaviors. Circular packaging solutions are anchored on the principles of "reduce-reuse-recycle", encompassing strategies such as reducing the prevalence of single-use plastic, advocating for material reuse and recycling, while enhancing the economic viability and quality of recycled plastic materials. Industry stakeholders are increasingly prioritizing the adoption of circular economy principles as the foundation for sustainable packaging practices, where materials are utilized efficiently, natural elements are incorporated into designs, and recyclability is emphasized to promote a more environmentally conscious approach [13].

The integration of environmentally sustainable materials in packaging aims to ensure that no detrimental impacts occur to product quality. A critical consideration is that packaging materials need to be manufactured from substances capable of upholding their primary function of safeguarding products, lightweight to reduce transportation costs, can be recycled or undergo biodegradation without posing harm to the environment. The adoption of sustainable packaging practices prioritizes the preservation of human health and environmental integrity through the selection of packaging materials. Within the framework of sustainability, efforts are being directed towards reducing both the volume of packaging materials used and the associated energy consumption, in alignment with the overarching objectives of resource efficiency and environmental protection [13].

SUSTAINABLE PACKAGING

Sustainable packaging is characterized by the following attributes: It should exhibit functionality, be safe to use, and promote the safe and healthfulness of products during its entire life cycle. It should aim to minimize packaging waste generation. It should be manufactured by adhering to good, manufacturing practices and when possible, by incorporating cutting-edge technologies. It should prioritize the optimization of materials and energy through innovative design methodologies. It should have lower GHG emissions and overall environmental impact. Preference should be given to the adoption of innovative and sustainable packaging materials that align with eco-friendly principles [7]. These packaging systems must be economically feasible and provide the desired consumer benefits if they are to compete with traditional packaging.

Using sustainable materials is one of the most reasonable ways to minimize packaging's impact on the environment. Traditional packaging materials are mostly produced using resources such as petroleum. Renewable resources such as wood, bamboo, sugar cane and even cork can be used to make sustainable packaging materials. Traditional materials require substantial energy in their production, which can increase greenhouse gas emissions [14]. Sustainable packaging can reduce our dependence on non-renewable resources [7]. Sustainable packaging involves not only environmentally friendly materials but also tailoring the packaging system design for maximum effectiveness. Lightweight and compact packaging helps reduce transportation costs while also reducing the waste. Efficient packaging can significantly impact a company's ability to reduce its GHG footprint, operating and transportation costs. This is especially important as e-commerce expands. The sustainable packaging arena is constantly changing and may include everything from [10]. Active packaging brings huge advances in the extension of product shelf-life and food degradation and losses reduction [15]. These developments not only help the environment, but also stimulate economic growth and offer companies new opportunities to stand out in the marketplace. Sustainable food packaging reduces the negative burden on packaging resources and packaging waste management, as well as reducing food losses and waste [10, 13].

Innovative packaging solutions to protect and enhance the shelf life of food needs the dynamism of research to create well-designed packaging that adapts to a specific foods requirement and has the needed functional features. Sustainable packaging materials must reduce energy usage in their life cycle production and have a reduced ecological footprint [16]. Innovative sustainable packaging aims to reduce the carbon footprint of packaging during life cycle, reduce food waste and maintain food quality [17]. It must also help control food safety concerns such as foodborne diseases and migration of chemical contamination from packaging to food [15].

SUSTAINABLE PACKAGING MATERIALS

There are a variety of food packaging materials that can be used safely, effectively, and sustainably. When choosing food packaging materials, several factors should be take into account: properties of packaging material, type of food to be packaged, food/package interactions, desired product life cycle, environmental conditions during handling, product end use, eventual package disposal and costs [18].

Paper, corrugated fiberboard

Paper and corrugated fiberboard packaging is mainly made from plant sources and break down naturally over time [19]. Paper packaging has advantages such as ease of use, low cost, lightness, utility and has a substrate conducive to providing information to consumers [19]. Paper has the highest recycling rate (4-7 times) among all packaging materials [20] and biodegradable material [19]. This feature makes it an environmentally friendly choice that reduces waste accumulation in landfills and minimizes the carbon footprint associated with disposal. However, ink and coating residues can negatively affect recyclability due to contain residual chemicals from the printing process [21]. This could create regulatory concerns if the recycled paper is to be in contact with food. Paper-based packaging is not a water or oxygen barrier and can therefore be easily damaged when it comes into contact with water or moisture [22]. Paper and corrugated fiberboard have advantages over plastic, metal and glass as packaging materials in terms of sustainability and cost. Paper based materials can be used in multi-layered and it is used by combining layers (enable sealability) with polyethylene (PE) and other polymers to improve its barrier function. While the combination of paper with other materials makes paper less sustainable, it increases its use [11]. For instance the Tetra Pak™ containers utilize several layers of material; paper increases its durability, PE improves its water transmission and acts as a binding layer, and as the inner seal layer, and the aluminum foil layers increases its oxygen barrier [20, 23].

The most important advantage of paper-based packaging materials is the perception that they benefit all stakeholders and the environment as a sustainable material. Trees or cellulose-derived plants are renewable resources through planned production and management. However, the manufacturing process of paper can lead to deforestation, water pollution, and chemical use, as well as generate substantial amounts of waste. Substantial energy and water are used in its initial production and can result in large amounts of waste water. Primary air emissions include carbon monoxide, sulfur dioxide, nitrogen oxides, volatile organic compounds and particulates [20].

Pulp fiber may be bleached using chemicals to improve the brightness and whiteness of the paper, thus increasing its printability and appearance. Standard bleaching uses chlorine, chlorine dioxide, or hydrogen peroxide and these chemicals can be released into the environment. More sustainable bleaching methods, such as the use of ligninolytic enzymes, are being investigated. Paper alone does not provide sufficient protection for food packaging due to its poor barrier properties, poor thermal adhesion, and durability in the present of moisture. Untreated paper-based materials are sensitive to moisture, oxygen, mineral oils and chemicals. Obtaining necessary barrier properties generally involves laminating materials with suitable barrier coatings (aluminum, ethylene vinyl alcohol-EVOH and polypropylene, others) to give the desired properties (increasing the barrier). Examples of such papers are waxed paper, a paper coated with wax to improve its barrier properties, and glycine paper, a paper produced at high density to provide resistance to oil. The barrier properties of papers are commonly controlled by the application of conventional petroleum-based derivatives such as polyethylene, polyvinyl chloride, polypropylene, polystyrene, waxes and/or fluorine-based derivatives as coatings [24]. The formulations purposely designed for multi-objective barrier properties, containing pullulan, sodium alginate, poly(vinyl alcohol), and minerals, lowered water vapor transmission rate by one order of magnitude [25]. Changes to paper processing methods can also improve its functional properties. Coating materials with various polymers can add needed properties [20]. Coating synthetic polymers onto paper-based materials reduces the biodegradability and recyclability of paper. Different biodegradable biopolymers such as polylactic acid (PLA), polyhydroxy alkanoates (PHA), starch, chitosan, natural rubber latex and polysaccharides can be used as sustainable barrier coatings in paper packaging applications [26]. Impregnating paper with additives during paper processing, such as colorants, optical brighteners, sizing or strengthening agents, is a common solution to improve paper properties for packaging [20].

Molded pulp packaging is a 100% biobased product generally produced from wastepaper and other natural resources that are compostable and biodegradable. Interest in sustainable packaging has led to increased use of molded pulp packaging. Molded pulp packaging can be used for clamshell packages or to protect fruits, vegetables, eggs and electronics during shipping [20]. By choosing paper packaging, businesses not only contribute to a greener future, but can also improve their brand image, meet legal requirements, and provide convenience to their customers. Adopting paper packaging is a step towards creating a more sustainable and environmentally conscious society. Interest in cellulose nanomaterials (CNs), which contain cellulose fragments with at least one dimension in the nanoscale, has increased. Compared to other nanoparticles, CNs are lighter, more environmentally friendly and have cost advantageous. CNs are attracting attention in sustainable packaging, thanks to features such as high strength, transparency, low thermal expansion and barrier properties [20, 27]. Cellulosic fibers have been added to plastic-based composites as fillers or reinforcements for many years, and in recent years the addition of CNs to bioplastics provides thermal stability, Improved chemical stability, and good mechanical and barrier properties while maintaining the transparency of the plastic [20].

The CNs practices are a good example of sustainable packaging. This means coating paper or bioplastics with CNs to improve properties. Adding CNs in thin layers to the paper surface reduces surface roughness. CNs added as coatings to paper and plastic have improved their O_2 and H_2O barrier properties. CN coatings on corrugated fiberboard or paper have not been shown to improve properties [20].

Plastic

Plastics are the most used materials to produce packaging in the food industry; about 320 million tons of plastic are produced annually, and the demand is growing every year [28]. Petroleum-based polymeric materials [polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET)] are widely used as packaging materials. Plastics have many advantages such as ease of shaping, versatility, good barrier properties, lightness, and affordable cost.

Most food products are needed in multilayer packaging materials with different properties. Each layer provides different properties to the multilayer structure including barrier (e.g., metalized film or aluminum foil) to water vapor, oxygen and other gases, adhesion, strength, printability, and compatibility with the food product. However, multilayer packaging is not recyclable because the layers are very difficult to separate [11, 21]. They are commonly used in the food industry due to their natural properties. However, plastic packaging materials have become a major concern due to their potential negative environmental impact [29]. Petroleum-based polymers are not biodegradable and have a recycling rate of less than only 10% (all the plastic ever produced) [30]. However, the recycling rates of some specific plastic (PET and HDPE was around 30%) were more significant [31]. Many chemical additives are also used in the production of plastics to provide flexibility, color and resistance to heat or sunlight. During production greenhouse gas emissions (CO_2, nitrous oxides, hydrofluorocarbons) may be released which could pollute the air, soils, and waters (seas and oceans) if improperly processed or recycled. Some may also be a source of microplastics that concern because of their widespread presence in the environment and the potential physical and toxicological risks they pose to organisms [32]. This is why the European Union (EU) Commission has set a target of reducing plastic waste by 55% by 2025 and that materials are 100% recyclable or reusable by 2030. However, this is difficult as not all plastic is collected for recycling and some types of plastic are easier to recycle than others. While some types of plastics (PET, HDPE, and PP) are more easily recycled than others. Some (PVC, LDPE, PS) are inherently inefficient to recycle, either economically or environmentally (not widely recycled), and thus are often used only once, causing environmental concern [12]. Retaining plastic industries in a circular economy would save the cost, time, energy of manufacturing and encourage innovation from used items while reducing dependence on new plastic manufacturing [33]. Therefore, to overcome these problems, great attention has been paid to environmentally friendly sustainable polymeric materials that will replace these materials and yet meet the needs of consumers [7].

Sustainable polymers are materials derived from renewable, recycled and waste carbon sources and their combinations that can be recycled, biodegraded, or composted at the end of their life. The preferred rational design of sustainable polymers is built around their synthesis from renewable monomers and that have been continuously (re)oriented for more than decade in their lifetime. Creating sustainable polymers from renewable monomers involves the associated production and use of new bio-based polymers that have the same chemical structure as their fossil-based analogues. Examples of these include bio-based polyethylene (bio-PE) and bio-based poly (ethylene terephthalate) (bio-PET) or polylactide (PLA) and poly(ethylene 2,5-furandicarboxylate) (PEF) [34].

Scientific efforts involving the design, synthesis and production of sustainable or green polymers have expanded tremendously over the last two decades. From a commercial standpoint, there are several leading candidates, each with their own sustainability metrics. Sugar is the most used raw material for these. Sugar fermentation produces the Polylactic acid (PLA), polyhydroxyalkanoates, poly (butylene succinate) (via biosuccinic acid), biopolyethylene (via bioethanol), biopolypropylene (via bioethanol), biopolyvinyl chloride (via bioethanol), polyethylene terephthalate (from bioethanol and conventional terephthalic acid) and polypropylene terephthalate (e.g. bio-1,3-propanediol and Sorona from conventional terephthalic acid). Other promising commercial polymers include polycarbonates made from isosorbide (chemically produced from glucose) or from copolymerization of carbon dioxide and epoxides [35]. Currently marketed bio sourced bioplastics (like Bio-PE, PLA, and more) use food sources like corn or sugar cane. Moreover, most of these bio-sourced bio-plastics are not biodegradable or home compostable (bio-PE, bio-PET) or are only suitable for industrial composting (PLA), which contributes to complicated waste management (separate collection of waste) [36].

PLA is a great business success story. One of the most visible is the scalable production process of PLA from corn via fermentation technologies (beverage containers in fast food restaurants). Twenty years ago, PLA was about 15-20 times more expensive than PET, but today PLA is only 15-25% more expensive than PET. However, PLA has some inherent disadvantages, such as a low glass transition temperature (55-60 °C) and reliable degradability, which is limited by stringent industrial composting conditions. The search for the ideal sustainable polymer continues [20, 35]. Researchers have and are focused on improving the mechanical and physical properties of biodegradable bio-based polymers such as proteins, polysaccharides, lipids and plant sources (e.g. cellulose, starch, chitosan, corn zein, whey protein, waxes, collagen, etc.).

In the next decade, sustainable polymer development will advance in various directions. Several strategies are outlined here, with retain significant potential for future optimization:

(1) Synthesizing water-degradable polymers that do not depend on narrow biological conditions for biodegradation, such as those that contain an acetal functional group.
(2) Insertion of specific functional groups into the polymeric main chain through functional group metathesis polymerization.
(3) Utilization of lignin-based aromatics to expand the operating temperature range of green polymers; and
(4) Development of new polymerization chemistry to use abundant, cheap, and renewable C1 feedstocks.

Consumer demand for functional and inexpensive green polymers is increasing. As global awareness and regulatory pressures on environmental sustainability intensify, bioplastics are increasingly seen as a viable solution to reduce dependence on fossil-based plastics and thus reduce potential pollution from plastics.

Bioplastics are generally divided into two main types based on their properties and source materials: bio-based (renewable sources such as corn starch, sugar cane or cellulose) and biodegradable (can be broken down into natural substances under certain conditions) plastics. One promising polymer is polyethylene furanoate, a 100% bio-based alternative to the petroleum-based PET used in the production of the beverage plastic bottles. Replacing the 250 ml and 500 ml bottles will lead to a significant reduction in greenhouse gas emissions. FDCA (2,5-furandicarboxylic acid), the main building block of PEF, can be produced from sugars (fructose), such as from wheat, corn and sugar beets. FDCA is polymerized with plant-based mono-ethylene glycol (MEG) to create a 100% plant-based PEF polymer. When fully developed technologically, PEF can also be produced from cellulose and therefore from agricultural and forestry waste. The resulting 100% bio-based (PEF), is recyclable and degradable and has superior barrier properties to CO_2 and oxygen (extending the shelf life of products) and higher mechanical strength (leading to thinner PEF packaging which requires fewer resources) compared to PET. It also has a 12°C higher heat resistance than PET. Made from sugar cane-based components, the material helps reduce carbon dioxide emissions and leaves a smaller environmental footprint. PEF can also be used in multilayer packaging when single-layer packaging is not sufficient to guarantee the required shelf life. It has been stated that reductions of approximately 37% in greenhouse gas emissions can be achieved by replacing 250 mL PET/PEF multilayer bottles containing 10% PEF with PET/PA bottles containing 7% PA (polyamide). Most importantly, the PET/PEF system is recyclable, whereas the system containing PA is not [37].

Beverage bottles and caps made from poly hydroxy alkanoates (PHA), another fully biodegradable biopolymer, are expected to enter the market soon. The use of PHA as a packaging material is expected to increase significantly in the coming years. Additionally, three new versions of recently developed PHA resin formulations for blown film, injection molding and thermoforming were released globally for customer evaluation in 2021. Fresh produce, such as fruits and vegetables are being packaged in flexible formats (e.g. films, trays, etc.) using bioplastics [20].

Coca-Cola aims to use three million fewer tons of virgin plastic from petroleum-based sources by 2025.This will reduce virgin plastic from fossil fuels globally by approximately 20% and support the common target of becoming net zero carbon by 2050 [38].

The future of bioplastics in sustainable packaging is bright, with the potential to contribute significantly to a more sustainable and circular packaging industry. Overcoming challenges and capitalizing on growth opportunities will be key to unlocking the transformative potential of bioplastics. There is increasing pressure on flexible film lamination (paper-film, paperboard-film, aluminum-film, paperboard-aluminum, paperboard-aluminum-plastic, plastic-based rigid multilayer) applications to improve the sustainability of products. In addition, the adhesive industry is looking to use special types of biobased adhesives and is focused on reducing molecular weight components of adhesives that can more easily pass from packaging to food. Using starch as a raw material in adhesive production has advantages such as low cost and non-toxicity, as well as renewability, biodegradability, and availability. Using natural resources or bio-based materials as adhesive raw materials can help future societies become less dependent on hazardous chemicals, volatile organic compounds and petroleum-derived chemicals; In addition to promoting safer working conditions.

The colorants (dyes, inks and pigments) most used in industries today are organic molecules obtained from petrochemicals and other chemicals that may cause significant damage to the environment. Natural colorants can be classified according to their color shade (red, etc.), origin (vegetable, animal, bacterial, fungal, etc.) or chemical structure as follows: flavonoid, isoprenoid, and nitrogen heterocyclic derivatives. Colorants produced from natural sources have advantages such as environmental friendliness, biodegradability and are thought to be harmful to human health. However, natural dyes are expensive due to limited natural resources. Natural colors have been associated with 3D printing technology (manufacturing). Additionally, 3D printing is an innovative way to produce complex shapes consisting of highly reflective bio-based mixtures, bio scaffolds, and reactive mixtures [39].

4D printing is a novel and advanced technique for manufacturing based on smart materials and involves a fourth dimension [21]. The 4D printing offers various advantages such as fast growth of smart and multi-materials, more flexible and deformable structures. The 4D enables the creation of self-assembling components that minimize packaging, transportation, and assembly-related waste and also increase environmental efficiency [40, 41]. Usually, prints are made with inkjet printing, screen printing, pad printing, and 3D printing systems. For the ink production, new production methods and materials that will minimize the dependence on petrochemical resources and the adverse environmental impacts should be used. Obtaining and using natural inks or dyes can provide an advantage to food packaging such as sustainable and environmentally friendly, favoring natural dyes over synthetic dyes [42].

Sustainable polymers face two main commercialization disadvantages: A limited effective processing in the product lifespan (recycling, reuse, biodegradability and compostability) and the high production process cost. To minimize the energy required to produce sustainable polymers, every step from monomer extraction to polymer processing must be focused on the use of renewable and minimal energy, the use of green solvents/catalysts, minimization of the number of conversion steps, increasing atom economy and, where possible, new and efficient polymerization methods that are innovative and optimize the overall process [43].

Glass

Glass is a permanent material that can be endlessly recycled, reused, and refilled, thus reducing waste and conserving natural resources. Glass has the best barrier protection compared to other packaging materials and acts as a safe barrier against external influences. In addition, it is a good packaging material for foods having a long shelf life. It is transparent, has good heat resistance. Glass is widely considered a recyclable and sustainable material. Glass is produced by melting and shaping a mixture of raw materials found in nature (silica, sodium carbonate and limestone/calcium carbonate) as well as recycled glass at a high temperature. Glass bottles are satisfactorily and commonly used in packaging beverages, water, and some dry products. Although the use of glass-based packaging materials is gradually decreasing, it will remain one of the safest packaging materials in the food and beverage industry.

Glass packaging, like all other packaging materials, has limitations such as being heavier than other packaging materials, brittle, and susceptible to thermal expansion or contraction. Glass packaging is not ideal for extreme temperatures. Glass can cause physical hazards if not handled properly during handling and transportation. When glass is damaged, it may break, compromising the safety of the product it contains. Fragility and weight, the most important disadvantages of glass packaging, have been partially eliminated by using technological innovations and it is possible to produce thinner and lighter glass packaging with the same performance [7].

Product innovations that allow the reduction in the thickness and weight of glass packaging reduce CO_2 emissions by 4-5%. Glass packaging production requires a lot of energy. Industry is working intensively to reduce carbon emissions at all stages of production. Glass recycling requires less energy than producing new glass from raw materials. The *Eco2Bottle*, *Wiegand-Glas*' wine bottle, is made from 93% recycled glass and is 20 percent lighter than similar bottles. Reducing the weight of each bottle directly impacts the logistics and transportation chain by reducing CO_2 emissions. The production and consequent recycling of ever-lighter glass packaging is efficient and provides significant environmental benefits by reducing CO_2 emissions and making it economically sustainable because less raw materials, and energy are needed and lower carbon emissions produced during transportation.

Echovai has produced the world's first reusable bottle from thermally hardened lightweight glass. This reduces logistical expenses and carbon emissions. The 0.33L reusable glass bottle has been introduced, with a weight reduction of around a third compared to the standard bottles (300 grams): Carbon emissions per bottle are only a quarter of that of the standard 0.33 lt reusable bottle [44]. Their reusability, recyclability, retention of product quality and longevity make them an excellent choice for those who want to reduce their carbon footprint. Reusable glass bottles have 85% less carbon emissions than disposable bottles, 75% less than disposable PET bottles, and 57% less than aluminum cans [45].

The glass industry aims and works towards a low-carbon future. It continues its work to minimize carbon emissions under the vision title "Ovens for the Future (F4F)". Investment should be made in low energy and low gas emission furnaces. It will be a major step to convert 50% or more of the furnaces used in glass packaging production into hybrid furnaces that use 80% renewable energy [46].

Metal

Metals used in food packaging include steel, tin and aluminum (cans, bottles, foil, and closures). Metal materials have advantages of durability (heat, light-UV, breakage-puncture), high barrier, durability and recyclability (easy to separate due to their magnetic nature) Recycled metals can be easily remelted and used to mould new packages [47]. However, disadvantages may include weight, processing costs and energy used at the same time, tin and aluminum from mining to production have their own life cycle considerations that need to be taken into account and carefully considered for environmental impact. For sustainability purposes, it is important that the production and recycling processes of metal packaging are based on environmentally friendly methods. Additionally, the design of the packaging should also be considered to reduce waste and facilitate recycling. Metal is widely recyclable. The production and recycling of metal is energy intensive [48]. Due to their capacity to be recycled, these materials are crucial parts of contemporary food packaging solutions since they not only guarantee the preservation of food quality and safety but also support sustainability initiatives [49].

Among all packaging metals, aluminum is the most used in packaging due to its structure. Aluminum's notable features include its low cost, light weight, flexibility, recyclability, and high heat resistance. Aluminum is a lightweight and corrosion-resistant metal. Aluminum is a very good conductor of electricity. Aluminum foil is used in closures, as a wrap and aluminum is used for beverage cans, tubs and trays, and blister packages that protect tablets and capsules, and areas as a layer in multi-layer structures for its barrier properties. It's easy shaping feature and decorative potential make aluminum a preferred material [48].

Steel is a durable, heavy and strong metal. Although steel is resistant to corrosive effects, it must be made more durable with coatings. Steel is used in the food industry as cans, g metal lids, metal drums and other container types [48].

Tin is a widely used material in metal plating. This coating is often used to coat steel to prevent corrosion when used for foodstuffs. [48]. Metal containers are extremely sustainable as they are the packaging material with the highest recycling rates worldwide, with 80% of tin packaging in Europe being recycled. This reduces energy consumption and eliminates raw material needs. Additionally, metal packaging helps reduce carbon emissions and contributes to the circular economy. In order to ensure the sustainability of metal packaging, features such as embossing, easy opening and lighter weight have been added [50].

INCREASING SUSTAINABILITY and INNOVATIVE FOOD PACKAGING MATERIALS

The main materials used for sustainable packaging are paper, paperboard, and corrugated fiberboard, bioplastic materials, glass, and metals. These materials are usually obtained from renewable resources, and including polymers obtained from microorganisms. These materials are recyclable, and/or reusable packaging that reduces disposable packaging waste. The efficient and effective practice of recycling can protect the environment from the pollution that may arise during the extraction of materials that are used in packaging industries [51]. With advancement of technologies, sustainable packaging has emerged in response to consumer preferences and environmental obligations. Studies on new techniques and new sustainable materials in packaging are increasing. Both new and higher-performance bioplastics are described as a breakthrough technology for sustainable packaging (Table 1).

Table 1. Top 20 sustainable packaging technologies by impact on sustainability and likelihood of adoption between 2018 and 2028 (adapted from [20])

Category	Technology
Recycling	• Near infrared process formality recovery • Deinking waste cardboard • Recyclable or biodegradable packaging • Design for recycling (airbags) • Effective cleaning of plastic waste for reuse Improved separation of multipolymer structures • Plastic-digesting bacteria
Innovative materials	• New biopolymers • Natural barrier coatings • Higher performance bioplastic • Edible packaging (bowls). • compostable packaging • Mono material barrier films
Design	• Smart tagging • Lightweight available packages • Hybrid meal delivery boxes. • Antimicrobial nanotechnology in active packaging
Other	• Big data analytics and blockchain • Innovation in covers • Sustainable protective packaging for transit and e-commerce • Free market packaging waste trade • Extended waste to energy schemes • Plates, trays and portion boxes made of corn starch, an alternative to polystyrene • Popcorn (rather than plastic cushioning) is a sustainable packaging option.

One of the currently most active research and development areas in packaging is bioplastics. Alternative cellulose-based feedstocks, such as bioplastics derived from bacteria and agricultural waste and other plant materials, are constantly being developed. For example, researchers Parrino, Fidalgo [52] have shown that polycarbonate can be produced from the synthesis of limonene, an extract from orange peels, and carbon dioxide. CNs are likely to be one of the most important new materials contributing to sustainable packaging. The versatility of CNs to serve as barrier films, coatings, reinforcements or additives for plastics raises the possibility they will become an important new packaging material. Additionally, the potential of PLA-based nanocomposite films to be used as packaging materials to extend the shelf life of water-sensitive food products has recently been demonstrated. Other natural coatings are expected to improve the properties of paper cups and providing durability to paper and corrugated fiberboard [27]. Another interesting innovation is packaging that is intended to be edible. The production of edible films with increased barrier properties by polymerizing biopolymers such as Chitosan, Whey Protein Isolate and Casein thru addition of cellulose nanocrystallites (whiskers) is being investigated [20]. New and high-performance bioplastics, that replace traditional bioplastics, will have an important place in sustainable packaging. Innovative materials continue to be developed at a rapid rate.

SUSTAINABLE FOOD PACKAGING REGULATIONS

Several countries have introduced regulations to reduce packaging waste and promote environmentally friendly alternatives. In general, the trend towards sustainable food packaging legislation and regulations is expected to continue and that more countries and regions introducing policies are taking measures to reduce waste and promote the promotion of a circular economy. The majority of most laws in the countries examined in the study also address the following end-to-end issues: packaging requirements, recyclability, expected main uses of packaging, packaging chain, including collection and sorting plans, schedules and determination of reuse - or recycling goals.

Regulations on Sustainable Food Packaging Materials in Different Countries

Regulations on sustainable food packaging materials vary across different countries, including Türkiye, EU, the US, the UK, Canada, and Japan (Table 2).

Türkiye's national government and its environmental agencies have begun taking measures to curb the consumption of certain single-use plastics through economic tools such as taxes, fees and container deposit systems, they are still not addressing the amount of imported waste entering the country. This regulation, entitled "Geri Kazanım Katılım Payına İlişkin Yönetmelik", introduced a recycling contribution fee (known as GEKAP) on the packaging of products sold domestically in early 2020 (Regulation 30995 on Recycling Contribution Rate). Environmental Law No. 2872 and Regulation 30829, Zero Waste Regulation, published in 2019, sets the goal of developing a zero-waste management system. Environmental Law No. 7153 – The procedures and principles regarding the collection of fees for plastic bags (2019). Some examples of recycling contribution shares for 2024 are: 0.25 TRY for each plastic bag, 19 TRY for each rubber tire, 4 TRY per kilogram for plastic packaging (except beverage containers and plastic bags), etc." According to Ordinance 30283 on the control of packaging waste (repealed) packaging must be "reused, recycled, recovered and designed and manufactured in a way that causes the least harm to the environment in the management and disposal phases that these processes include". Türkiye's National Waste Management and Action Plan sets targets for diverting waste from landfills and increasing its recycling targets, and is in line with EU Directive 2015/720, which targets plastic bag consumption. The general legal framework for the regulation of packaging and plastic waste is established by Environmental Law No. 2872 [53].

The European Parliament and the Council regulate the rules for environmentally friendly food packaging in the EU. In order to make all plastic packaging recyclable by 2030, the European Strategy for Plastics was adopted in January 2018. Member states have agreed to adopt stricter regulations by 2030 (Table 2).

Table 2. Regulations on sustainable packaging materials in some countries [54].

Country	Regulations
Türkiye	• Regulation 30995 on Recycling Contribution Rate, recycling contribution fee – GEKAP • Environmental Law No. 2872, (2019) • Regulation 30829, Zero Waste Regulation, (2019)
European Union	• The heart of EC legislation on packaging and packaging waste is Directive 94/62/EC (Directive 94/62/EC, 1994). • Regulation (EC) No. 1935/2004 and Regulation (EC) No. 2023/2006 on food contact/packaging materials • Regulation (EC) 282/2008 on recycled plastic materials for food packaging • Directive (EU) 2018/852 amendments of Directive 94/62/EC on packaging and packaging waste EPR EU's Circular Economy (2020) • Directive (EU) 2019/904 on single-use plastics • EN 13427:2004d Requirements in the field of packaging and packaging waste • EN 13428:2004d Prevention through source reduction • EN 13429:2004d reuse; EN 13430:2004d recovered through material recycling • EN 13431:2004d requirements for packaging energy recovery • EN 13432:2004d requirements for packaging recoverable through composting and biodegradation.
United States of America	• Federal Food, Drug, and Cosmetic Act (FDCA) (Title 21) (1938) • Guidance for Industry: Use of Recycled Plastics in Food Packaging: Chemistry Considerations (2021)
United Kingdom	• Producer Responsibility Obligations (Packaging Waste) Regulations (2007) • The Plastic Packaging Tax (2022) • Packaging (Essential Requirements) Regulations (2015) • Deposit Return Scheme (2023)
Canada	• Ban on single-use plastic items • Canadian Standards Association developed standard • CAN/BNQ-0017-088 for compostable plastics
Japan	• Food Sanitation Act (1947) • Plastic Resource Circulation Act (Act No. 60 of 2021) • Containers and Packaging Recycling Act (1995)

Less packaging and restrictions on certain packaging formats the agreement sets packaging reduction targets (5% by 2030, 10% by 2035 and 15% by 2040) and obliges EU countries to reduce the amount of plastic packaging waste in particular. Ban on the use of "forever chemicals" In order to prevent adverse health effects. Final distributors of take-away drinks and food in the catering industry would be obliged to offer consumers the option of bringing their own container. They would also have to strive to offer 10% of products in a reusable packaging format by 2030[54].

United States Federal Regulations:

- The US Environmental Protection Agency (EPA) promotes sustainable packaging through initiatives like the Sustainable Materials Management Program (SMM), which encourages the use and reuse of materials over their life cycles [55].
- State-Level Regulations: States such as California, New York, and Oregon have enacted laws to ban single-use plastic bags and introduced Extended Producer Responsibility (EPR) legislation to manage packaging waste responsibly [55, 56].
- The US FDA believes that as long as the recycled polymer is kept separated from the food by a reliable barrier of virgin polymer or other suitable material such as aluminum foil, there is no need to worry about possible migration of contaminants into food use. The US FDA has issued safety notices for PET and HDPE containers with a layer of recycled material and a layer of virgin material that comes into contact with food. While EC 10/2011 sets criteria for the composition of new plastic materials, the separate regulation of EC 2022/1616 sets out recycled plastic materials and items intended to come into contact with food (EUR-Lex, 2022).

The UK's environmental packaging regulations aim to promote more sustainable packaging and reduce waste sent to landfill:

- United Kingdom Extended Producer Responsibility (EPR): The UK has implemented EPR policies, requiring businesses to collect data on their packaging to comply with regulations and promote sustainable practices.
- Plastic Packaging Tax: The UK introduced a tax on plastic packaging with less than 30% recycled content to incentivize the use of recycled materials and reduce waste.
- Single-Use Plastic Bans: The UK has banned certain single-use plastic items and implemented policies to reduce plastic waste and promote recycling [57].

Regulations in Canada;

- Canada Single-Use Plastics Prohibition Regulations (SUPPR): Canada aims to achieve zero plastic waste by 2030 through the prohibition of manufacturing, importing, and selling many single-use plastic items [56].
- Extended Producer Responsibility (EPR): Provinces like Ontario and British Columbia have implemented EPR programs for packaging materials, requiring businesses to take responsibility for recovering and recycling their packaging waste [55].

Japanese Regulations:

- Japan Food Sanitation Law (1947): Japan has regulations focusing on packaging and product safety, ensuring that food packaging materials meet certain standards [54].
- Containers and Packaging Recycling Act (1995): This act promotes the recycling of packaging materials and encourages sustainable practices in the packaging industry [54].

There is no international treaty that imposes legal obligations on contracting states regarding sustainability. Several international bodies - from the General Assembly itself to the United Nations Environment Program (UNEP) to the United Nations Development Program (UNDP) - cooperate and work with states and non-state actors on sustainability issues; there is no international agency mandated with monitoring and enforcement powers. Regulations alone are obviously not enough. Through strict enforcement and monitoring, national and supranational entities, regional authorities, companies, communities and individuals become responsible actors.

These regulations highlight the global commitment to reducing packaging waste and promoting sustainable practices in the food packaging industry (Table 2).

FOOD COMPANIES AND SUSTAINABILITY STUDIES

According to the SÜTAŞ 2022 Sustainability Report

1. Under the headings of Carbon Management and climate change, 80% of the needs of their production facilities were met by renewable energy sources.
2. They grew approximately 43 thousand tons of organic matter in their fields.
3. They carried out R&D studies by breeding productive breeds on their farms.
4. Sustainable dairy farming training was provided to approximately 19 thousand employees working in the companies.
5. They reduced the amount of plastic material they used in their packaging by 153 tons (Sütaş Sustainability Reports, 2022).

According to ŞİŞECAM 2022 Sustainability Report (Table 3)

1. Approximately 7 million m^3 of water was recycled.
2. Obtaining demineralized water
3. The project of collecting and recycling packaging glass waste is being carried out.
4. Thanks to waste glass collection projects, between 500 and 1000 tons of glass were recycled.
5. Low-e coated glass has been developed, making it possible to control heat and light.
6. Household items are produced from 100% recycled glass materials.
7. Primary school students were raised with recycling training.

8. Approximately 5 million people were reached through social media and information was given about the sustainability of glass (Sustainability Reports, 2022).

Table 3. Packaging product examples for Şişecam and Ardgah Group sustainability efforts

Company Name	Packaging Type	Product Type
ŞİŞECAM	Glass	Low E-Glass Products Antimicrobial V-Block Coating Solar Panel Glasses Lightweight Glass Packaging Glass fiber
ARDGAH	Glass	Efficient Oven NextGen Hybrid Oven

According to ARDGAH GLASS 2022 Sustainability Report (Table 3)

Ardgah Glass examples of packaging products for sustainability studies continues to work on the NextGen Hybrid Furnace, which aims to reduce GGE by 60 percent [58].

CONCLUSION

Sustainability is becoming ever more important across all aspects of the economy. Sustainable packaging is an active development and research area with increasingly innovative ideas. Growing consumer demand around the globe for sustainability initiatives and emerging regulations will continue to drive packaging towards sustainability. Companies are under pressure to re-think and re-design their packaging systems. Bio-based materials such as paper and board and bioplastics are ideally positioned to capture some of this market growth. However, there are still challenges to fully realize the replacement of petroleum-derived packaging with bio-based packaging. It is anticipated that ongoing research and technological advances, innovative new materials, consumer education, improvements in recycling and increased commercial availability will continue to contribute to increased acceptance of these alternative materials. Many countries and regions have implemented regulations that require sustainable eco-friendly alternatives packaging materials or set targets to cut down on packaging waste.

Sustainable packaging and may bring us closer to a more sustainable future. Although there are many benefits to eco-friendly or sustainable food packaging, the cost of switching to these food packaging solutions can be expensive, especially for many small businesses. It can lead to higher costs in the production and other parts of the operation. Whether consumers are willing to compromise and pay more poses a clear challenge for companies. Sustainable packaging should remain as broadly encompassing as possible.

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